NUTRITION AND METABOLISM IN SPORTS, EXERCISE AND HEALTH

JIE KANG

SECOND EDITION

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Nutrition and Metabolism in Sports, Exercise and Health

The second edition of *Nutrition and Metabolism in Sports, Exercise and Health* offers a clear and comprehensive introduction to sport and exercise nutrition, integrating key nutritional facts, concepts and dietary guidelines with a thorough discussion of the fundamental biological science underpinning physiological and metabolic processes. Informed by the latest research in this fast-moving discipline, the book includes brand new sections on, amongst others:

- Cellular structure for metabolism
- Alcohol and metabolism
- Uncoupling protein and thermogenesis
- Dietary guidelines from around the world
- Nutrient timing
- Protein synthesis and muscle hypertrophy
- Protein supplementation
- Ergogenic effects of selected stimulants
- Nutritional considerations for special populations
- Dehydration and exercise performance

Each chapter includes updated pedagogical features, including definitions of key terms, chapter summaries, case studies, review questions and suggested readings. A revised and expanded companion website offers additional teaching and learning features, such as PowerPoint slides, multiple-choice question banks and web links.

No book goes further in explaining how nutrients function within our biological system, helping students to develop a better understanding of the underlying mechanisms and offering the best grounding in applying knowledge to practice in both improving athletic performance and preventing disease. As such, *Nutrition and Metabolism in Sports, Exercise and Health* is essential reading for all students of sport and exercise science, kinesiology, physical therapy, strength and conditioning, nutrition or health sciences.

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Nutrition and Metabolism in Sports, Exercise and Health

Second Edition

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Good health and strong performance: nutrition connection

Nutrition and its impact on health and performance are of crucial importance. Nutritional deficiencies were once a major health challenge in most developed countries. However, what we are facing now is the fact that nutritional abundance contributes to many of today's health problems. In order to choose foods that satisfy your personal and cultural preferences, but also contribute to a healthy diet and prevent diseases, you must have information about what nutrients you require, what role they play in health and performance, and what foods contain them. You must also be able to judge the validity of the nutrition information you encounter. Your body uses the nutrients from foods to make all its components, fuel all its activities, and defend itself against diseases. How successfully your body handles these tasks depends, in part, on your food choices and your understanding of the principles of nutrition. Nutritious food choices support a healthy and strong body.

What is nutrition?

Nutrition is a science that links foods to health and diseases. It studies the structure and function of various food groups and the nutrients they contain. It also includes the biological processes by which our body consumes food and utilizes the nutrients. The science of nutrition also concerns the psychological, social, cultural, economic, and technological factors that influence which food we choose to eat.

Why study nutrition?

Nutrition has played a significant role in your life, even from before your birth, although you may not always be aware of it. It will continue to affect you in major ways depending on the foods you select. Not meeting nutrient needs in younger years make us more likely to suffer health consequences in later years. At the same time, taking too much of a nutrient can be harmful. A poor diet and a sedentary lifestyle are known to be the major risk factors for life-threatening chronic diseases such as heart disease, hypertension, diabetes, and some forms of cancer, which together amount to two-thirds of all deaths in North America (Table 1.1). Such linkage between lifestyle and chronic diseases is, in part, mediated through the development of **obesity**, a condition attributable to a positive energy balance (i.e., energy brought in via foods > energy expended via physical activities). Most of these chronic diseases mentioned above are the **comorbidity** (a diseased state, disability or poor health) of obesity. In fact, obesity is considered to be the second cause of preventable death in North America (Figure 1.1).

Table 1.1 Leading causes of death in the US

Rank	*Cause of death*	*Total deaths (%)*
1	Heart diseases (primarily coronary heart disease)[1,2]	29
2	Cancer[1,3]	23
3	Cerebrovascular diseases (stroke)[1,2,3]	7
4	Chronic obstructive pulmonary diseases and allied conditions (lung diseases)[3]	5
5	Accidents and adverse effects[2]	4
6	Diabetes[1]	3
7	Influenza and pneumonia	3
8	Alzheimer's disease[1]	2
9	Kidney diseases[1,3]	2
10	Blood-borne infections	1

Source: Center for Disease Control and Prevention, National Vital Statistical Report, Final data.

Notes
1 Causes of death in which diet plays a part.
2 Causes of death in which excessive alcohol consumption plays a part.
3 Causes of death in which tobacco use plays a part.

Needless to say, your food choice today can affect your health tomorrow. Understanding nutrition will allow you to make wise choices about foods you consume, thus improving health and fitness. You must be aware, however, that making appropriate food choices is not an easy task, and can be influenced by many outside factors. For example, a decision should be preceded by your answer to questions such as: Are you active? Are you an athlete? Are you planning a pregnancy? Are you trying to prevent the physical decline that occurs with aging? Did your mother die of a heart attack? Does cancer run in your family? Are you trying to lose weight or eat a vegetarian diet? Is your heritage Asian, African, European, or Central or South American? In order to choose foods that satisfy your personal and cultural preferences but also contribute to a healthy diet and prevent diseases, you must not only have information about what nutrients you require

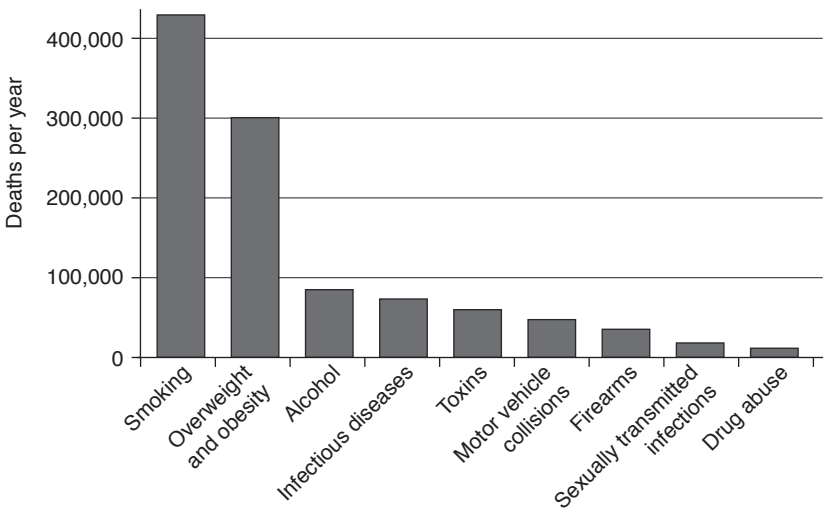

Figure 1.1 Leading preventable causes of death

and what foods contain them, but also understand the role nutrients play in the body and how they may contribute to an enhanced physical performance or a pathological process that leads to a disease. You must also be able to judge the validity of the nutrition information you encounter. Should you be taking antioxidant supplements, eating fat-free foods, or drinking calcium-fortified orange juice? Should you believe the story or testimony you saw on the news about a weight loss diet or protein supplement? Filtering out the worthless requires a solid understanding of principles of nutrition, the nutrient contents of foods, the function of nutrition in the body, as well as the process by which scientists study nutrition.

Role of nutrition in fitness, health, and performance

The two primary factors that influence one's health status are genetics and lifestyle. Most chronic diseases have a genetic basis. The Human Genome Project, which deciphered the DNA code of our 80,000 to 100,000 genes, has identified various genes associated with many chronic diseases. Genetically, females whose mothers had breast cancer are at increased risk for breast cancer, while males whose fathers had prostate cancer are at increased risk for prostate cancer. Scientists now have the ability to analyze the genetic basis underlying various diseases, and such information may be used to evaluate individual susceptibility. For individuals with genetic profiles predisposing them to a specific chronic disease, genetic therapy may provide an effective treatment or cure.

Genetic influence, as well as lifestyle, may play an important role in the development of chronic disease. Recent studies have suggested that lifestyle, particularly one that incorporates a healthy diet and exercise, may provide the best hope for living a healthier and longer life. It is the most proactive and cost-effective approach to addressing an increasing prevalence of these chronic diseases in our society. Over the years, scientists in the field of epidemiology have identified a number of lifestyle-related risk factors. A **risk factor** is a health behavior or pre-existing condition that has been associated with a particular disease, such as cigarette smoking, physical inactivity, stress, insulin resistance, hyperlipidemia, etc. Proper diet and exercise have been found to be able to reduce many of these risk factors, thereby preventing diseases. It is believed that such a healthier lifestyle can also intertwine with one's genetic profile. In other words, what you eat and how you exercise may influence your genes.

Proper nutrition is an important component in the total training program of the athlete. The consumption of energy-containing nutrients such as carbohydrate provides the fuel necessary for increased biological work. Nutrient deficiencies can seriously impair performance, whereas nutrient supplementation may delay fatigue and improve performance. Nutritional status can be a major factor differentiating athletes of comparable genetic endowment and state of training. Regular training allows athletes to improve their performance by enhancing biomechanical skills, sharpening psychological focus, and maximizing physiological functions. However, gains in these areas can be directly potentiated or undermined by various dietary factors associated with the athlete. For example, losing excess body fat will enhance biomechanical efficiency; consuming carbohydrate during exercise may prevent hypoglycemia and thus fatigue; and providing adequate dietary iron may ensure optimal oxygen delivery to the working muscles.

Sports nutrition represents one of the fast-growing areas of study within recent years. It is the study and practice of nutrition and diet as it relates to athletic performance. Although scientists have studied the interactions between nutrition and various forms of sports and physical activities for more than a century, it is only within the past few decades that extensive research has been undertaken regarding the specific guidelines and recommendations to athletes. Louise Burke, a prominent sports nutritionist from

Australia, defines sports nutrition as the application of eating strategies to promote good health and adaptation to training, to recover quickly after each exercise training session, and to perform optimally during competition. A sound understanding of sports nutrition enables one to appreciate the importance of adequate nutrition, and to critically evaluate the validity of claims concerning specific dietary modifications and nutrient supplements to enhance physique, physical performance, and exercise training responses. Knowledge of the nutrition-metabolism interaction forms the basis for preparation, performance, and recovery phases of intense exercise or training. Many physically active individuals, including some of the world's best athletes, obtain nutritional information from magazine and newspaper articles, advertisements, training partners, and testimonials from successful athletes, rather than from well-informed and well-educated coaches, trainers, physicians, and fitness and sports nutrition professionals. Far too many cases have been reported where athletes devote considerable time and energy striving for optimum performance, only to fall short due to inadequate, counterproductive, and sometimes harmful nutritional practices.

Nutrition plays a significant role in one's life. "Good nutrition" encompasses more than preventing nutrient deficiencies or inadequacies related to diseases. It also forms the foundation of one's fitness, physical performance, and overall well-being. As you gain understanding about your nutritional habits and increase your knowledge about optimal nutrition, you will have the opportunity to reduce your risk for many common diseases, to sustain the demands placed upon your body, and to stay healthy, fit, and strong.

Chemical and biological aspects of nutrition

The human body comprises carbon, hydrogen, oxygen, nitrogen, and a few other assorted elements. When jointed together, these elements are transformed into large, functional, and life-sustaining compounds, or molecules, such as proteins, carbohydrates, lipids, and nucleic acids. Cells carry out the vital functions of life. Our bodies are made up of trillions of cells which differ vastly in size, function, and shape. Cells of similar structure and function form tissues. Four different types of tissues comprise over 40 organs, which makes up 11 unique organ systems. Understanding the chemical compounds found in food and their many roles in the biological processes of life is fundamental to the study of nutrition.

Chemistry of life

The organization of atoms into molecules, molecules into macromolecules, macromolecules into cells, cells into tissues, tissues into organs, and organs into organ systems is illustrated in Figure 1.2. This entire circuitry is made of and fueled by the nutrients contained in food. Before discussing the concept of nutrients, it is important to have a basic understanding of chemistry – the science that deals with composition, structure, properties, and change of matter.

The sub-microscopic particles, called **atoms**, are the fundamental units that make up the world around us. The atom itself consists of still smaller units: uncharged neutrons and positively charged protons, both housed in the center or nucleus of the atom. Electrons, which have a negative charge, orbit the nucleus of an atom in spaces called shells. In most cases, the net positive charge of protons is balanced by an equal number of electrons. When the number of protons having positive charges equals the number of electrons having negative charges, atoms is neutral. However, it is possible for atoms to gain or lose electrons. When this occurs, the numbers of protons and electrons are no

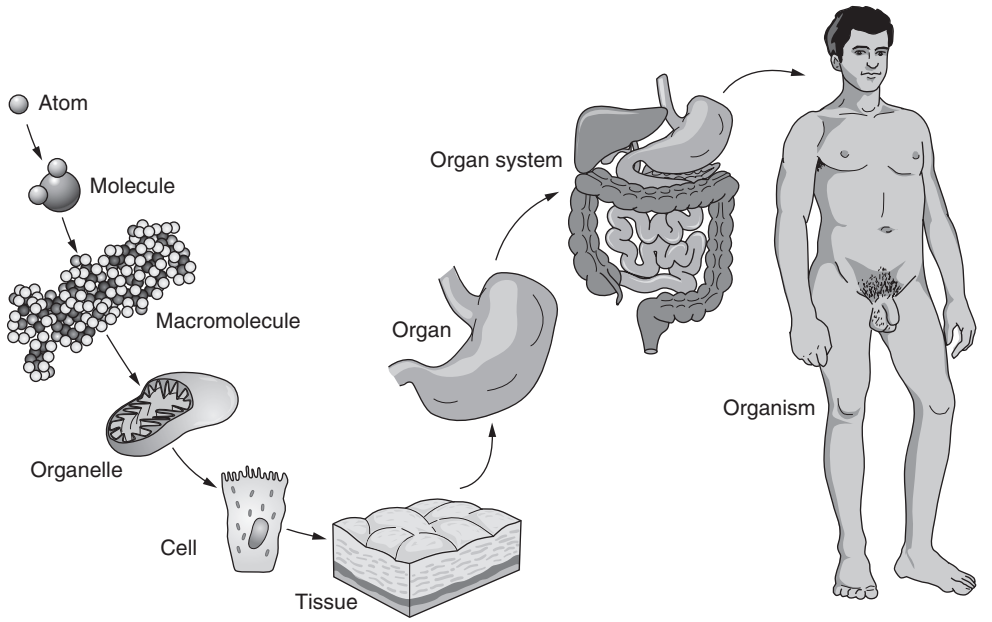

Figure 1.2 Levels of organization in organisms
Source: Shier *et al.* (2010). Used with permission.

longer equal. As a result, an atom has a net positive or negative charge. Atoms that have an unequal number of protons and electrons are called **ions**. However, it is important to note that molecules can also be ions. For example, the hydroxide ion (OH-), which consists of a hydrogen and oxygen atom, has an overall net negative charge. An ion with a net positive charge is called a cation, and an ion with a net negative charge is called an anion. Important ions found in the human body include sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), chloride (Cl^-), iodide (I^-), and fluoride (F^-).

An **element** is defined as a pure substance made up of only one type of atom. There are approximately 92 naturally occurring elements, 20 of which are essential for human health. In fact, just six elements – carbon, oxygen, hydrogen, nitrogen, calcium, and phosphorous – account for 99 percent of total body weight. These basic elements comprise macromolecules, such as proteins, carbohydrates, lipids, and nucleic acids, found in living systems.

When two hydrogen atoms and one oxygen atom are chemically joined together, a molecule of water is formed. A **molecule** is defined as two or more atoms joined together by chemical bonds. A molecular formula, such as H_2O, is used to describe the number and types of atoms present in a molecule. For examples, glucose, an important source of energy in the body, has a molecular formula of $C_6H_{12}O_6$. These numbers and letters tell us that a molecule of glucose consists of 6 carbon, 12 hydrogen, and 6 oxygen atoms. Some molecules, such as oxygen (O_2) consist of only one type of atom. Most molecules, however, are made up of different atoms. Molecules composed of two or more different atoms, such as water (H_2O) and glucose ($C_6H_{12}O_6$), are called compounds.

The acidity of a molecule or compound is a frequent issue of discussion in nutrition. Grapefruits and lemons have a sour taste, whereas baking soda tastes bitter. Pure water has no taste at all. These taste differences are attributed, in part, to the level of acidity,

ranging from acidic (such as citrus) to neutral (such as water), or alkaline (such as baking soda). By definition, **acids** are molecules that release hydrogen ions (H^+) when dissolved in water, whereas **bases** are molecules that release hydroxide ions (OH^-). The increased concentration of hydrogen ions causes the pH, a numeric scale that measures acidity, of a solution to decrease or to become more acidic. Conversely, a basic substance such as sodium hydroxide (NaOH) releases sodium (Na^+) and hydroxide (OH^-) ions when dissolved in water. When sodium hydroxide is dissolved in an acidic solution, the hydroxide ions (OH^-) combine with hydrogen ions (H^+) present in the solution to form water. As a result, the concentration of hydrogen ions (H^+) in the solution decreases, thus increasing pH. Such a neutralizing process partly explains how a buffer works in an effort to resist changes in pH in the body. A **buffer** is a solution that reacts with both acids and bases to maintain a constant pH. Sodium bicarbonate is the most common buffer found in the body. It helps maintain pH in a tight range and provide an effective defense against acidosis and alkalosis.

Cells and their components

All living organisms consist of cells, the "building blocks" of the body. Cells are surrounded by a protective cell membrane. Within the cell, small membrane-bound structures called organelles carry out specialized functions that are critical for life (Figure 1.3).

Cell membranes (also called plasma membranes) provide a boundary between extracellular (outside the cell) and intracellular (within the cell) environments. In addition, cell membranes regulate what goes into or out of cells. The unique structure of cell membrane can be compared to that of a sandwich. In cell membranes the "slices of bread" are made up of two phospholipid sheets, called the phospholipid bilayer. Whereas a sandwich may have meat or cheese between the slices of bread, the phospholipid bilayer is embedded with protein, carbohydrate, and cholesterol. More details on the unique arrangement of phospholipid bilayer are given in Chapter 3. Proteins associated with cell membranes have both structural and functional roles. These include transporting materials into and out of cells, acting as receptors for other molecules, and providing cell-to-cell communication. Cholesterol, a type of lipid, is important for membrane stability and fluidity. Carbohydrates form hair-like projections, which act like antennae and enable cells to recognize and interact with each other. Carbohydrates also help communicate conditions outside of cells to the intracellular compartment.

Cells are like microscopic cities; they are full of activity. Like cities, cells have factories for manufacturing products, local transport systems to move materials, a system for waste disposal, and so on. These activities are carried out in cells by structures called **organelles**, which are distributed in the gel-like intracellular matrix called **cytoplasm**, or **cytosol**. Each organelle is responsible for a specific function. For example, **mitochondria** serves as a power station, converting energy-yielding nutrients (glucose, fatty acids, and amino acids) into a form of energy that cells can use. Another organelle, called the cell **nucleus**, houses the genetic material DNA, which provides the "blueprint" for protein synthesis. Information encoded in the DNA is transported out of the nucleus to organelles called **ribosomes**, a factory site for protein synthesis. Some ribosomes are attached to a network of membranous tubules called the **endoplasmic reticulum** (ER), which serves as the "work surface" for protein synthesis. Ribosomes give the ER a bumpy appearance. Therefore, protein-producing ER are referred to as the rough endoplasmic reticula. Other ER are involved with lipid synthesis. These ribosome-free ER have a smooth appearance and are thus referred to as the smooth endoplasmic reticula. Finally, substances made by the two forms of endoplasmic reticula are sent for further processing

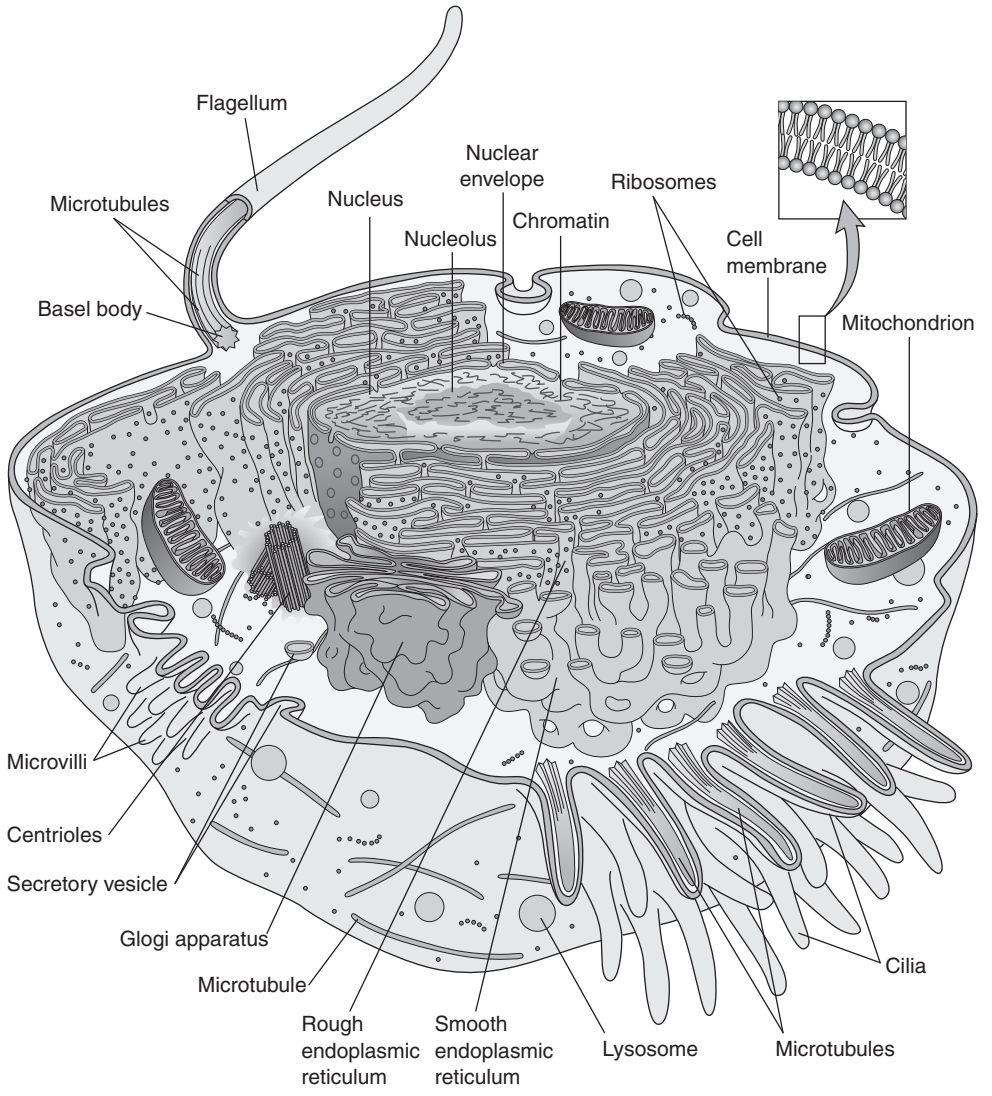

Figure 1.3 Cellular structure

Source: Shier *et al.* (2010). Used with permission.

to another organelle called **Golgi apparatus**. The Golgi apparatus modifies proteins and lipids, resulting in the finished product. Once complete, these substances can be used by the cell or packaged into vesicles and exported from the cell via exocytosis.

Nutrients

People eat to receive nourishment. Do you ever think of yourself as a biological being made up of carefully arranged atoms, molecules, cells, tissues, and organs? Are you aware of the activity going on within your body even as you sit still? The atoms, molecules, and cells of your body continually move and change, even though the structures

of your tissues and organs and your external appearance remain relatively constant. Your skin that has covered you since your birth is replaced entirely by new cells every seven years. The fat beneath your skin is not the same fat that was there a year ago. Your oldest red blood cell is only 120 days old, and the entire lining of the digestive tract is renewed every three days. To maintain these ongoing changes you must continually replenish, from foods, the energy and the nutrients you deplete in maintaining the life of your body.

What are nutrients?

Nutrients are substances contained in food that are necessary to support growth, maintenance, and repair of the body tissues. Nutrients may be further assigned to three functional categories: (1) those that provide us with energy; (2) those that are important for growth, development, and maintenance; and (3) those that regulate biological processes to keep body function running smoothly. Nutrients can also be divided into essential and nonessential. **Essential**, also referred to as indispensable, nutrients are those substances necessary to support life but they must be supplied in the diet because the body cannot make them or make them in a large enough quantity to meet needs. Protein, for example, is an essential nutrient needed for growth and maintenance of the body tissues and the synthesis of regulatory molecules. Food also contains nutrients considered **nonessential**. Some of these are not essential to sustain life but have health-promoting properties. For example, a phytochemical (e.g., carotenoids) found in orange, red, and yellow fruits and vegetables is not essential but may reduce the risk of cancer. Others are required by the body but can be produced in sufficient amounts to meet needs. For example, lecithin, which is needed for nerve function, is not an essential nutrient because it can be manufactured by the body.

Classes of nutrients

Chemically, there are six classes of nutrients: carbohydrates, lipids, proteins, vitamins, minerals, and water. Carbohydrates, lipids, and proteins provide energy to the body and are thus also referred to as **energy-yielding nutrients**. Along with water, they constitute the major proportion of most foods. They are also known as **macronutrients** because they are required in relatively large amounts. Their requirements are measured in kilograms (kg) or grams (g).

Carbohydrates include sugars such as those found in table sugar, fruit, and milk, and starches such as those in vegetables and grains. Sugars are the simplest form of carbohydrate, and starches are more complex carbohydrates made up of many sugars linked together. Carbohydrates provide a readily available source of energy to the body. Most fiber is also carbohydrate. It cannot be completely broken down, so it provides a little energy. However, it is important for gastrointestinal health. Fiber is found in vegetables, fruits, legumes, and wholegrains.

Lipids, commonly referred to as fats and oils, provide a storage form of energy. Lipids in our diets come from foods that naturally contain fats, such as meat and milk, and from processed fats, such as vegetable oils and butter, that we add to food. Most lipids contain fatty acids, some of which are essential in the diet. Lipids contain more energy than carbohydrates. However, energy utilization from lipids is limited because it involves a more complex metabolic process. The amount and type of lipid in our diet affects the risk of cardiovascular and metabolic diseases as well as certain types of cancer.

Protein, such as that found in meat, fish, poultry, milk, grains, and legumes, is needed for growth and maintenance of body structure, and regulation of biological processes. It rarely serves as an energy source. Protein is made up of units called amino acids. Twenty

or so amino acids are found in food, and some of them are considered essential. Dietary protein must meet the need for the essential amino acids. Most North Americans eat about one and a half to two times as much protein as the body needs to maintain health. This amount of extra protein in the diet is generally not harmful – it reflects the standard of living and dietary habits – but one should keep in mind that the excess can contribute to the storage of fat.

Vitamins and minerals, on the other hand, are referred to as **micronutrients** because they are needed in small amounts in the diet. The amounts required are expressed in milligrams (mg) or micrograms (μg). They do not provide energy, but many help regulate the production of energy from macronutrients. They also play unique roles in processes such as bone growth, oxygen transport, fluid regulation, and tissue growth and development. Vitamins and minerals are found in most of the foods we eat. Fresh foods are good natural source of vitamins and minerals, and many processed foods have micronutrients added to them during manufacture. For example, breakfast cereals are a good source of iron and B vitamins because they are added during processing. While processing can cause nutrient loss due to light, heat, and exposure to oxygen, with the addition of certain nutrients, frozen, canned, and otherwise processed foods can still be good sources of vitamins and minerals. In today's diet, vitamin and mineral supplements are also a common source of micronutrients.

Water makes up the sixth class of nutrients. About 60 percent of the human body is water. Although sometime overlooked as a nutrient, water has numerous vital functions in the body. It acts as a solvent and lubricant, as a vehicle for transporting nutrients and wastes, and as a medium for temperature regulation and chemical reactions. Water is considered a macronutrient and is required in a large quantity in the daily diet. The average man should consume about 3000 ml or 13 cups of water and/or other fluids containing water every day. Women need close to 2200 ml or about 9 cups per day.

Together, the macronutrients and micronutrients provide energy, structure, and regulation. These functions are important for growth, maintenance, repair, and reproduction. Each nutrient provides one or more of these functions, but all nutrients together are needed to maintain health (Table 1.2).

Chemical composition of nutrients

The simplest nutrients are the minerals. Each is a chemical element; its atoms are all alike. As a result, its identity never changes. For example, iron may change its form, but it remains iron when food is cooked, when a person eats the food, when iron becomes part of a red blood cell, when the cell is broken down, and when the iron is lost from the body by excretion. The next simplest nutrient is water, a compound made up of two elements: hydrogen and oxygen. Minerals and water are **inorganic nutrients** because they contain no carbon.

The other four classes of nutrients – carbohydrates, lipids, proteins, and vitamins – are more complex. In addition to hydrogen and oxygen, they all contain carbon, an element found in all living species. They are therefore called **organic compounds**. Proteins and vitamins also contain nitrogen and may contain other elements as well (Table 1.3).

The energy-yielding nutrients

Carbohydrates, lipids, and proteins provide the fuel or energy required to maintain life, and are therefore considered as energy-yielding nutrients. If less energy is consumed than is needed, the body will burn its own fat as well as carbohydrate and protein to

Table 1.2 Nutrient functions in the body

Nutrients	*Major function*	*Example*
Carbohydrates	Energy	Muscle glycogen is stored carbohydrate that fuels the body cells.
Lipids	Energy	Fat is the most plentiful source of stored fuel in the body.
	Structure	The membranes that surround each cell are primarily lipids.
	Regulation	Estrogen is lipid hormone that helps regulate the reproductive cycle in women.
Proteins	Energy	Proteins may be used for energy when consumed in excess or carbohydrate becomes depleted.
	Structure	Proteins are an important part of body tissues, including muscles, tendons, and ligaments.
	Regulation	Insulin is a protein that helps regulate blood glucose concentrations.
Vitamins	Regulation	B vitamins help regulate energy metabolism using macronutrients.
Minerals	Structure	The minerals calcium and phosphorus make bones and teeth solid and hard.
	Regulation	Sodium helps regulate blood volume.
Water	Structure	Water makes up nearly 60% of body weight.
	Regulation	Water evaporated as sweat helps reduce body temperature.

meet the energy needs. If more energy is consumed than is needed, the extra is stored as body fat. The energy contained in foods or needed for all body processes and activities is measured in kilocalories (abbreviated as kcal) or kilojoules (abbreviated as kj). The term "calorie" is technically 1/1000 of a kilocalorie, but when spelled with a capital "C" it indicates kilocalories. For example, the term "Calories" on food labels actually refers to kilocalories or kcal. When completely broken down in the body, a gram of carbohydrate or protein provides 4 kcal. One gram of lipid provides 9 kcal, and lipids, therefore, have a greater energy density than either carbohydrates or proteins (Table 1.4).

One other substance which yields energy is alcohol. Alcohol is not considered a nutrient because it interferes with the growth, maintenance, and repair of the body, but it does yield energy. When metabolized in the body, alcohol contributes about 7 kcal per gram (Table 1.4).

Table 1.3 Chemical elements in the six classes of nutrients

Nutrients	*Carbon*	*Hydrogen*	*Oxygen*	*Nitrogen*
Carbohydrate	✓	✓	✓	
Lipids	✓	✓	✓	
Proteins[1]	✓	✓	✓	✓
Vitamins[2]	✓	✓	✓	
Minerals[3]				
Water		✓	✓	

Notes
1 Some proteins also contain the mineral sulfur.
2 Some vitamins also contain nitrogen and other elements.
3 Each mineral is a chemical element.

Table 1.4 Energy content of macronutrients and alcohol

	Kilocalories/gram	*Kilojoules/gram*
Carbohydrate	4	16.7
Lipids	9	16.7
Proteins	4	37.6
Alcohol	7	29.3

Note
1 kilocalorie = 4.18 kilojoules.

Most foods contain all three energy-yielding nutrients, as well as water, vitamins, and minerals. For example, meat contains water, fat, vitamins, and minerals as well as protein. Bread contains carbohydrate, water, a trace of fat, a little protein, and some vitamins and minerals. Only a few foods are exceptions to this rule, the common ones being table sugar (pure carbohydrate) and cooking oil (pure fat).

How much of each nutrient do we need?

In order to support life, an adequate amount of each nutrient must be consumed in the diet. The exact amount that is optimal is different for each individual. It depends on genetic makeup, lifestyle, and overall diet. A person with a genetic predisposition to a disease needs to consume different amounts of certain nutrients to maintain health than does a person with no genetic risk of the disease. Individuals who smoke cigarettes need more vitamin C than non-smokers. Athletes or those who are more active need more carbohydrate and the total daily energy than do their less active counterparts. The amount of each nutrient required is also dependent on the other nutrients and non-nutrient substances present in the diet. For example, adequate consumption of fat is essential for the absorption of vitamin A. The amount of iron absorbed is affected by the presence of vitamin C and calcium. Thus, it is difficult to make generalized recommendations about how much is enough or not enough without considering both individual needs and overall diet.

Consuming either too much or too little of one or more nutrients or energy can cause **malnutrition**. Malnutrition is often interpreted as **under-nutrition** or a deficiency of energy and nutrients. Under-nutrition may occur due to reduced intake of energy and nutrients, increased requirements, or an inability to absorb or use nutrients. It can cause weight loss, poor growth, an inability to reproduce, and, if severe enough, death. Iron deficiency is a form of under-nutrition commonly seen in young children, adolescents, and some women owing to their increased need for iron. Vitamin B12 deficiency is a risk for older adults because the ability to absorb B12 in the stomach decreases with age. When under-nutrition is caused by a specific nutrient deficiency, the symptoms often reflect the body functions that rely on the deficient nutrient. For example, vitamin D is necessary for bone growth and maintenance; a deficiency of vitamin D can result in osteoporosis. Vitamin A is necessary for vision; a deficiency of vitamin A can result in blindness.

Over-nutrition is also a form of malnutrition. When food is consumed in excess of energy requirements, the excess is stored as body fat. Some fat is necessary for insulation, protection, and as an energy store, but an excess of body fat increases the risk for high blood pressure, heart disease, diabetes, and other chronic diseases. These conditions can take months and years to manifest themselves. When excesses of specific nutrients are consumed, an adverse or toxic reaction may occur. Because foods generally do not contain high enough concentrations of nutrients to be toxic, most nutrient toxicities often result from the overuse of specific supplements.

What is reliable nutritional information?

The science of nutrition is young but fast growing, especially as our society has become more health-conscious over recent years. We are bombarded with nutrition information, and much of it reaches us through television, the internet, radio, newspapers, and magazines. Although dieticians, nutritionists, and physicians are viewed as the most valuable source of nutrition information, it seems that we get most of our food and nutrition information from mass media. Much of the information is reliable, but some can be misleading. One should always be aware that the motivation for news stories is often to sell subscriptions, improve ratings, or make news headlines more enticing, rather than to promote the nutritional health of the population. Some nutrition and health information originates from food companies. It is usually in the form of marketing designed to sell existing or target new products. Sifting through the information and distinguishing the useful from the useless can be overwhelming. However, an understanding of the process of science and how it is used to study the relationship between nutrition and health or performance will allow you to develop the knowledge and ability needed to judge the validity of nutritional products.

Scientific methods

Advances in nutrition are made using the scientific method. The scientific method offers a systematic, unbiased approach to evaluating the relationships between food and health or performance. As shown in Figure 1.4, the first step of the scientific method is to make an observation and ask questions about that observation. For example, "What foods or

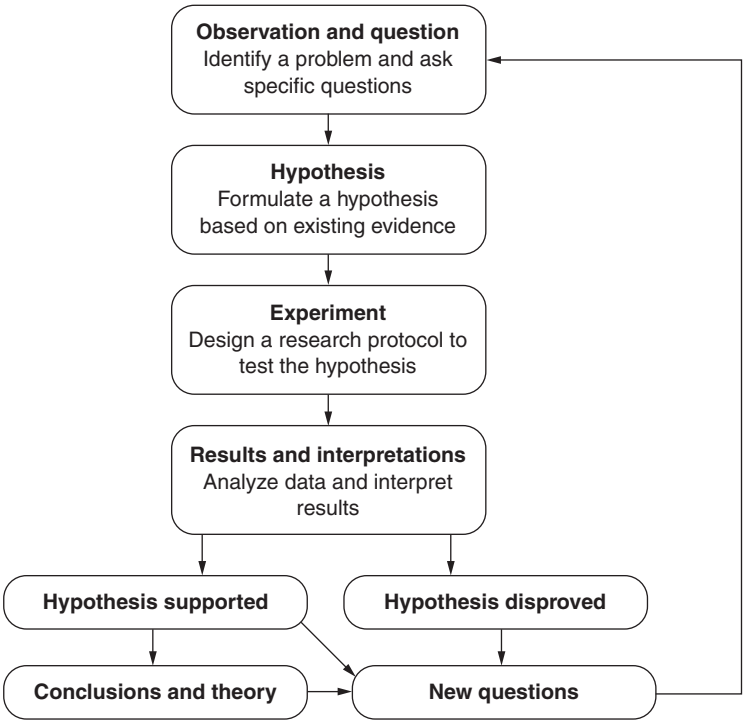

Figure 1.4 The scientific method of inquiry

nutrients might protect against the common cold?" In search of an answer, scientists then make a scientific explanation or **hypothesis**, such as "Foods rich in vitamin C reduce the number of common colds." Once a hypothesis has been proposed, experiments can be designed to test it. The experiments must provide objective results that may be measured and repeated. If the results fail to prove the hypothesis to be wrong, a theory or a scientific explanation can be established. Even a theory that has been accepted by the scientific community for years can be proved wrong. This changeover allows the body of knowledge to grow, but it can be confusing as old or more conventional theories give way to new ones.

A well-conducted experiment must collect quantifiable data using proper experimental controls and the right experimental population. For example, body weight and blood pressure are parameters that can be measured reliably. However, feelings and perceptions are more difficult to assess. They can be quantified with standardized questionnaires, but individual testimonies or opinions, referred to as anecdotal, cannot be measured objectively, and thus are considered non-quantifiable.

Experimental controls ensure that each factor or variable studied can be compared with a known situation. They are often accomplished by using a **control group** that serves as a standard of comparison for the treatment being tested. A control group is treated the same way as the experimental groups, except that no experimental treatment is given. For example, to investigate the effect of creatine supplementation on strength and power performance, the experiment group consists of athletes consuming the creatine monohydrate, whereas the control group consists of athletes of similar age, gender, and training backgrounds eating similar diets and following similar workout regimens, but not consuming the creatine product.

A **placebo** can be used to further minimize differences between experimental and control groups. The placebo should be identical in appearance and taste to the actual treatment but have no therapeutic value. By using a placebo, participants in the experiment would not know if they are receiving the actual treatment. When subjects do not know which treatment they are receiving, the study is called a **single-blind study**. Using a single-blind study helps prevent the expectations of subjects from biasing the results. For example, it the athletes think they are under the actual treatment, they develop a higher expectation of themselves and as a result work harder during the treatment and/or testing period. Errors may also occur if investigators allow their own desire for a specific result to affect the interpretation of the data. This type of error can be avoided by using a **double-blind study** in which neither the subjects nor the investigators know who is in which group until the results have been analyzed.

Another important issue with the scientific method is to determine a sample size. To be successful, an experiment must show that the treatment being tested causes a result to occur more frequently than it would occur by chance. To ensure that chance variation between the two groups does not influence the results, the sample size must be large. If there is a change occurring by chance in one member of a group of five, such change can easily alter the whole group's average; but if such change occurs in one member of a group of 500, it will not overly affect the group average. Fewer subjects are needed to demonstrate an effect that rarely occurs by chance, and vice versa. For example, if only one person in a million can improve muscle power without creatine supplementation, then the experiment to see if creatine supplementation increases muscle power would require only a few subjects to demonstrate the effect. If one in four athletes can improve muscle power without creatine supplementation, then more subjects are needed for the study. The sample size needed to show the effect of an experimental treatment may be determined using statistical methods before a study is conducted.

Types of research

Several types of research techniques have been used to determine nutrient requirements, to learn more about nutrient metabolism, and to understand the role of nutrition in health, fitness, and performance. These research techniques may be broadly divided into two categories: **epidemiological research** and **experimental research**.

Epidemiological research involves studying large populations in order to suggest a relationship between the two or more variables. For example, epidemiological research has helped scientists observe that those who consume a diet high in fat were more likely to develop heart disease. There are various forms of epidemiological research. One general form uses retrospective techniques. In this case, individuals who have a certain disease are identified and compared with a group of peers who don't have the disease. Researchers then trace the lifestyle history and eating habits of both groups to determine whether dietary practices or other factors may have increased the risk for developing the disease. Another general form of epidemiological research uses a prospective technique. In this case, individuals who are free of a specific disease are identified and then followed for years, during which time their lifestyle behaviors, including eating habits, are scrutinized. As some individuals develop the disease and others don't, the researchers are then able to discern whether dietary behaviors may increase the risk of the disease.

Epidemiological research helps scientists identify important relationships between variables, but it does not prove a cause-and-effect relationship. For example, in epidemiological studies that revealed an association between high fat intake and heart disease, experimental research typically involved examining the incidence of heart disease and dietary factors cross-sectionally using multiple groups of subjects or longitudinally using the same group of subjects, and the conclusion was drawn based on the observation that those with high fat intake also have high incidences of heart disease. However, questions could be raised as to whether high fat intake directly causes heart disease. To answer these questions, one may hypothesize that a high fat intake predisposes one to cardiovascular disease, but this hypothesis must then be tested by studies containing tightly controlled experimental approaches.

Experimental research constitutes another common form of research in nutritional science. The observation and hypotheses that come from epidemiological research may be tested in experimental research, which will then allow scientists to establish a cause-and-effect relationship. This type of research actively intervenes in the lives of individuals, and usually involves studying a smaller group of subjects that receive a treatment or placebo under either tightly controlled or free-living conditions. In such studies, often called intervention studies, an independent variable (cause) is manipulated so that changes in dependent variables (effect) may be studied. For example, if it is determined by epidemiological research that individuals who eat a low-fat diet have a lower incidence of heart disease, an intervention trial may be designed with an experimental group that consumes a diet lower in fat than is typical in the population and a control group that consumes the typical higher fat diet, while both groups are kept the same in terms of other aspects of lifestyle, i.e., total caloric intake and participation in physical activities. The two groups can be monitored and compared to see if the dietary intervention affects the incidence of heart disease.

The experimental approach appears to be a common choice in studies that examine the effect of nutrition on sports performance, though they are of a shorter time frame compared to those studies that investigate the relationship between nutrition and health. In addition, most sports nutrition studies are conducted in a laboratory with tight control of extraneous variables. In order to make research findings more relevant to

actual sports, many of these studies also attempt to use laboratory protocols designed to mimic the physiological demands of the sport. Although a research study that possesses both the rigorous control of its experimental design and ability of its findings to be readily applied is always preferable, achieving both simultaneously has often been found to be difficult.

Judging nutritional information

Knowledge relative to all facets of life, the science of nutrition included, has increased phenomenally over recent years. As knowledge advances, new nutritional principles are developed. Sometimes, established beliefs and concepts must give way to new ideas, which then result in a change in recommendations. It has long been suggested that margarine is better for you than butter. However, current research indicates that it is just as bad for you. Indeed, nutrition is a fast-growing discipline in part because consumers are now taking a greater responsibility for self-care and are eager to receive food and nutrition information. Such an increase in societal interest creates opportunities for nutritional misinformation to flourish. According to the American Dietetic Association, the media are consumers' leading source of nutrition information, but news reports of nutrition research often provide inadequate depth for consumers to make wise decisions. Consumers must also be aware of the fact that certain individuals may capitalize on research findings for personal financial gain. For example, isolated nutritional facts may be distorted or results of a single study may be used to market a specific nutritional product.

Just as scientists use the scientific method to extend their understanding of the world, each of us can use an understanding of how science is conducted to evaluate nutritional claims. Claims associated with nutrition products are always appealing. It is up to us as consumers to decide whether and how we should accept them. In judging the validity of a nutritional product, one should always question whether product claims make sense, and, if they do, where they come from. If a product is claimed to change body composition in only one or two weeks without altering diet and exercise habits, common sense should tell you that it is too good to be true. If the claim seems to be reasonable, then the question becomes where it came from. Was it a personal testimony, a government recommendation, or advice from a health professional? Was it the result of a research study? Was such a research study found in a peer-reviewed journal?

Claims that come from individual testimonies have not been tested by experimentation, and therefore it cannot be assumed that similar results will occur in other people. On the other hand, government recommendations regarding healthy dietary practices are developed by a panel of scientists who use the results of well-controlled research studies to develop recommendations for the population as a whole. The government provides information about food safety and recommendations on food choices and the quantities of specific nutrients needed to avoid nutrient deficiencies and excesses and to prevent chronic diseases. These recommendations are used to develop food-labeling regulations and are the basis for public health policies and programs.

Results from research studies published in peer-reviewed journals are generally considered accurate because these studies have been scrutinized by the scientific community to determine their validity and reliability. On the other hand, results presented at conferences or published in popular magazines, although they may be legitimate, should be viewed with caution, as they are usually not subject to the scrutiny of others who are experts in the same field. Even well-designed, carefully executed, peer-reviewed experiments can be a source of misinformation if the experimental results are interpreted incorrectly or if the implications of the results are exaggerated. For example, a mineral called Boron has been considered as an ergogenic aid because a study shows that consuming boron

enhances blood testosterone levels in those with boron deficiency. Nevertheless, supplementing boron to increase testosterone levels in those with boron deficiency does not necessarily mean that to increase boron consumption in those with a normal boron level to begin with will have the same effect. It is usually true that once an adequate intake of a nutrient is achieved, consuming it in excess is ineffective. A study which shows that rats fed a diet high in vitamin E live longer than those consuming less vitamin E could lead people to conclude that vitamin E supplementation can prolong one's life. However, can results from this animal study be extrapolated to humans? Just because rats consuming diets high in vitamin E live longer does not mean that the same is true for humans.

The best means to evaluate claims of enhanced health and sports performance made by nutritional products or practices is to possess a good background in nutrition and a familiarity with the experimental process of high-quality research. However, this may not be possible for all individuals who are seeking nutritional products. For those who have a minimal background in nutrition, it is recommended that the following be used as basic guidelines in evaluating the claims made for a nutritional product or practice. If the answer to any of following questions is yes, then one should be skeptical of such a product and investigate its real efficacy before investing any money in it.

- Is its claim too good to be true?
- Does the product promise quick improvement in health and physical performance?
- Is it advertised mainly through the use of anecdotes, case histories, or individual testimonials?
- Are currently popular personalities or star athletes featured in its advertisements?
- Does the person or organization who recommends it also sell the product?
- Is it expensive, especially when compared to the cost of equivalent nutrients that may be obtained from ordinary foods?
- Does it use the results of a single study or poorly controlled research to support its claims?

Summary

- Nutrition is a science that links foods to health and diseases. It studies the structure and function of various food groups and the nutrients they contain. It also includes the biological processes by which our body consumes food and uses the nutrients contained therein.
- Your food choice today may affect your health tomorrow. Understanding nutrition will allow you to make wise choices about foods you consume, thus improving health and fitness.
- Proper nutrition is an important component in the total training program of the athlete. Nutrient deficiencies can seriously impair performance, whereas nutrient supplementation may delay fatigue and improve performance. Nutritional status can be a major factor differentiating athletes of comparable genetic endowment and state of training.
- Sports nutrition represents one of the fastest-growing areas of study over recent years. It is the study and practice of nutrition and diet as it relates to athletic performance.
- The human body consists of carbon, hydrogen, oxygen, nitrogen, and a few other assorted elements. When joined together, these elements are transformed into large, functional, and life-sustaining compounds, or molecules, such as proteins, carbohydrates, lipids, and nucleic acids. Understanding the chemical compounds found in food and their many roles in the biological processes of life is fundamental to the study of nutrition.

- All living organisms consist of cells, the "building blocks" of the body. All human cells are surrounded by a cell membrane. Inside the cell membrane are the cytosol or cell fluid and organelles that perform the functions necessary for cell survival. Common organelles found in most cells are cell nuclei, mitochondria, endoplasmic reticulum, ribosomes, Golgi apparatus, and lysosomes.
- Nutrients are substances contained in food that are necessary to support growth, maintenance, and repair of the body tissues. The six classes of nutrients include carbohydrate, lipids, proteins, vitamins, minerals, and water.
- Carbohydrates, lipids, and proteins provide the fuel or energy required to maintain life, and are therefore considered to be energy-yielding nutrients. The energy contained in foods or needed for all body processes and activities is measured in kilocalories (abbreviated as kcal) or kilojoules (abbreviated as kj).
- Epidemiological research and experimental research are the two types of research frequently used in the study of nutrition. The former involves studying large populations in order to suggest a relationship between the two or more variables, whereas the latter involves studying a smaller group of subjects that receive a treatment or placebo under either tightly controlled or free-living conditions.
- In judging the validity of a nutritional product, one should always question whether product claims make sense and, if they do, where they come from. Claims that come from individual testimonies have not been tested by experimentation. However, claims supported by research studies published in peer-reviewed journals are generally considered accurate.

Case study: judge the scientific merit of a nutritional product

The picture on the nutritional product was eye-catching. A good-looking couple were running along a beach. He was shirtless and had impressive upper-body muscle mass. She was in a tight-fitting sundress and had a perfect figure and long, blonde hair. The product was advertised as a weight loss supplement. This advertisement also included a statement saying, "Research studies show that this supplement helps people lose weight and feel less fatigued." After seeing this advertisement, Jill wrote to the company and asked about the research that had been conducted to develop this product. She received the company's newsletter, which discussed two research studies.

In the first study, 12 obese subjects were divided into two groups, with one group being given the supplement and the other receiving no supplement. The 12 subjects were all consuming a liquid diet of 800 kcal daily. These subjects were living in an experimental research ward where they had no access to food other than the liquid diet. It was found that over a four-week study period, subjects receiving the supplement lost more weight than those who did not receive it.

In the second study, eight healthy male college students were studied in two groups. They were asked to follow their regular physical activities, but one group took the supplement while the other received a placebo. The study was double-blind. After three weeks, subjects were asked how energetic they felt during a workout and throughout the day. It was found that the subjects who received the supplement reported high energy levels and less fatigue than those who did not.

Questions

- What were the strengths of these experiments?
- What was wrong with each of these experiments?
- Should consumers be encouraged to use this supplement as a weight loss aid? Why?

Review questions

1 What is nutrition? What is sports nutrition?
2 What is a nutrient? Name the six classes of nutrients found in foods. What is an essential nutrient?
3 Which nutrients yield energy and how much energy do they yield per gram? How is energy measured?
4 Describe the chemical structure of a cell membrane.
5 What are the functions of (1) ribosome, (2) endoplasmic reticulum, and (3) Golgi apparatus.
6 Why are mitochondria sometimes called the "powerhouses" of the cells?
7 Describe the types of research methods often used in acquiring nutrition information.
8 List steps involved in scientific method.
9 What is a control group? What is a placebo? What is a double-blind study?
10 What factors should be considered in judging nutrition claims?

Suggested reading

1 American Heart Association Nutrition Committee, Lichtenstein AH, Appel LJ, Brands M, Carnethon M, Daniels S, Franch HA, Franklin B, Kris-Etherton P, Harris WS, Howard B, Karanja N, Lefevre M, Rudel L, Sacks F, Van Horn L, Winston M, Wylie-Rosett J (2006) Diet and lifestyle recommendations revision 2006: a scientific statement from the American Heart Association Nutrition Committee. *Circulation*, 114: 82–96.
Improving diet and lifestyle is a critical component of the American Heart Association's strategy for cardiovascular disease risk reduction in the general population. This document presents recommendations designed to meet this objective.
2 Cordain L, Eaton SB, Sebastian A, Mann N, Lindeberg S, Watkins BA, O'Keefe JH, Brand-Miller J (2005) Origins and evolution of the Western diet: health implications for the 21st century. *American Journal of Clinical Nutrition*, 81: 341–354.
This article discusses an evolutionary discordance between our ancient, genetically determined biology and the nutritional, cultural, and activity patterns of contemporary Western populations, which may explain some of the lifestyle-related diseases we are experiencing today.
3 Hoffman DJ, Policastro P, Quick V, Lee SK (2006) Changes in body weight and fat mass of men and women in the first year of college: a study of the "freshman 15." *Journal of American College Health*, 55: 41–45.
This original investigation was designed to measure changes in body weight and percentage of body fat among first-year college students, and to address a common but often undocumented myth among college students that there is a high risk of gaining 15 pounds of weight during freshman year.

Glossary

Acids molecules that release hydrogen ions (H^+) when dissolved in water.
Atoms sub-microscopic particles and the fundamental units that make up the world around us.
Bases molecules that release hydroxide ions (OH^-) when dissolved in water.
Buffer a solution that reacts with both acids and bases to maintain a constant pH.
Control group a group of subjects who serve as a standard of comparison for the treatment being tested in a research experiment.
Cytosol gel-like intracellular matrix within a cell.
Double-blind study a research design or setup in which neither the subjects nor the investigators know who is in which group until the results have been analyzed.

Element a pure substance made up of only one type of atom.
Endoplasmic reticulum a network of membranous tubules within the cytoplasm.
Energy-yielding nutrients referred to as carbohydrates, lipids, and proteins that provide energy to the body.
Epidemiological research research that involves studying large populations in order to suggest a relationship between two or more variables.
Essential also referred to as indispensable which describes those nutrients necessary to support life but which must be supplied in the diet because the body cannot make them or make them in a large enough quantity to meet needs.
Experimental research research that actively intervenes in the lives of individuals and usually involves studying a smaller group of subjects that receive a treatment or placebo under either tightly controlled or free-living conditions.
Golgi apparatus an organelle responsible for transporting, modifying, and packaging proteins and lipids into vesicles for delivery to targeted destinations.
Hypothesis a proposed scientific explanation for a phenomenon.
Inorganic nutrients nutrients that contain no carbon, such as minerals and water.
Ion a charged atom or molecule due to an unequal number of electrons and protons.
Macronutrients nutrients required by the body in relatively large amounts often measured in grams (g), such as carbohydrate, lipids, and protein.
Malnutrition often interpreted as under-nutrition, but also includes a condition of over-nutrition.
Micronutrients nutrients required by the body in relatively small amounts often measured in milligrams (mg) or micrograms (μg), such as vitamins and minerals.
Mitochondria an organelle, also referred to as a powerhouse, responsible for converting food energy into biologically usable energy.
Molecule two or more atoms joined together by chemical bonds.
Morbidity a diseased state, disability, or poor health.
Nonessential also referred to as dispensable which describes those nutrients required by the body but which can be produced in sufficient amounts to meet needs.
Nucleus an organelle that houses the genetic material DNA.
Nutrients substances contained in food necessary to support growth, maintenance, and repair of the body tissues.
Nutrition a science that links foods to health and diseases.
Obesity a condition attributable to a positive energy balance (i.e., energy brought in via foods > energy expended via physical activities).
Organelles microstructures within a cell.
Organic compounds nutrients that contain carbon in addition to hydrogen and oxygen, such as carbohydrates, lipids, proteins, and vitamins.
Over-nutrition a form of malnutrition that occurs when food is consumed in excess of energy requirements.
Placebo a sham or simulated treatment that is identical (i.e., in appearance and taste) to the actual treatment but that has no therapeutic value.
Ribosome a factory site for protein synthesis within the cytoplasm.
Risk factor a health behavior or pre-existing condition that has been associated with a particular disease, such as cigarette smoking, physical inactivity, stress, insulin resistance, hyperlipidemia, etc.
Single-blind study a research design or setup in which subjects do not know which treatment they are receiving.
Sports nutrition the study and practice of nutrition and diet as it relates to athletic performance.
Under-nutrition a form of malnutrition that occurs due to reduced intake of energy and nutrients, increased requirements, or an inability to absorb or use nutrients.

2 Macronutrients
Carbohydrates

Contents

Key terms

- Alcohol dehydrogenase pathway
- Amylopectin
- Blood alcohol concentration
- Cirrhosis
- Ethanol
- Fiber
- Galactose
- Gluconeogenesis
- Glycemic index
- Insoluble fiber
- Lactase
- Maltose
- Moderate alcohol use
- Oligosaccharides
- Starch
- Type 1 diabetes
- Amylase
- Amylose
- Cellulose
- Disaccharides
- Fermentation
- Fructose
- Glucagon
- Glucose
- Glycogen
- Insulin
- Lactose
- Microsomal ethanol-oxidizing system
- Monosaccharides
- Soluble fiber
- Sucrose
- Type 2 diabetes

Introduction

A student, quietly reading a textbook, is seldom aware that within his brain cells billions of **glucose** molecules are splitting to provide the energy that permits him to learn. Similarly, a marathon runner, bursting across the finish line, seldom gives thanks to the glycogen which his muscles have devoured to help him finish the race. Your brain needs carbohydrates to power its activities. Your muscles need carbohydrates to fuel their work too. Together, glucose and its stored form **glycogen** often provide more than a half of all the energy used by the brain, muscles, and other body tissues. The rest of the body's energy comes mainly from fat.

People don't eat glucose and glycogen directly; they eat food rich in carbohydrates. Then their bodies convert the carbohydrates mostly into glucose for immediate energy and into glycogen for reserve energy. Except for lactose from milk and a small amount of glycogen from animals, plants provide the major source of carbohydrate in the human diet. All plant foods (i.e., wholegrains, vegetables, legumes, and fruits) provide ample carbohydrates. Although everyone eats carbohydrates, the amount and type consumed often depend on the wealth and prosperity of the society. In more affluent countries, animal foods become more affordable, so the intake of fat and protein increases. For example, the typical intake of carbohydrates accounts for nearly two-thirds of the energy in the diet in developing countries, while it accounts for only about half of the energy intake in more economically developed countries.

Not all carbohydrates are created equal. Some are referred to as simple and well-refined carbohydrates (i.e., candies, cookies, and cakes), while others are considered complex and less processed (i.e., wholegrains, vegetables, and legumes). Many people mistakenly think of carbohydrates as "fattening" and believe that diets high in carbohydrates contribute to the epidemic of obesity. They avoid them when trying to lose weight. Such a strategy can be counterproductive if the carbohydrates being consumed are most complex. In fact, most dieticians and nutritional scientists consider consuming foods rich in complex carbohydrates and fibers to be one of the most important components of a healthy diet, not only for its potential in preventing certain chronic diseases but also as an integral part of a proper diet to lose excess body fat in the long run.

Chemical basis of carbohydrates

Chemically, carbohydrates contain carbon (carbo), as well as hydrogen and oxygen in the same proportion as in water (hydrate). Combining atoms of carbon, hydrogen, and oxygen forms a simple carbohydrate or sugar molecule with the general formula $C_6H_{12}O_6$, although the number of carbon can vary from three to seven. Six-carbon sugars are also referred to as hexoses. Accordingly, three-carbon sugars are trioses, four-carbon sugars are tetroses, five-carbon sugars are pentoses, and seven-carbon sugars are heptoses. Of these varieties, the hexose sugars interest nutritionists the most. In these molecules, atoms of C, O, N, and H are linked by chemical bonds between these atoms. Atoms form molecules in ways that satisfy the bonding requirement of each atom. For example, as shown in Figure 2.1, each carbon atom has four binding sites that link to other atoms, including carbons. Carbon bonds not linked to other carbon atoms accept hydrogen (with one binding site), oxygen (with two binding sites), or a hydrogen–oxygen combination (OH) referred to as hydroxyl.

Classification of carbohydrates

Carbohydrates have been typically classified as simple carbohydrates that include **monosaccharides** and **disaccharides** and complex carbohydrates that include **oligosaccharides** and **polysaccharides**. Saccharide means an organic compound containing a sugar or sugars. It is the number of saccharides or sugars linked within the molecule that distinguishes each carbohydrate category.

Monosaccharides

The basic unit of carbohydrate is a single sugar molecule, a monosaccharide (mono means one). When two monosaccharides combine, they form a disaccharide (di means

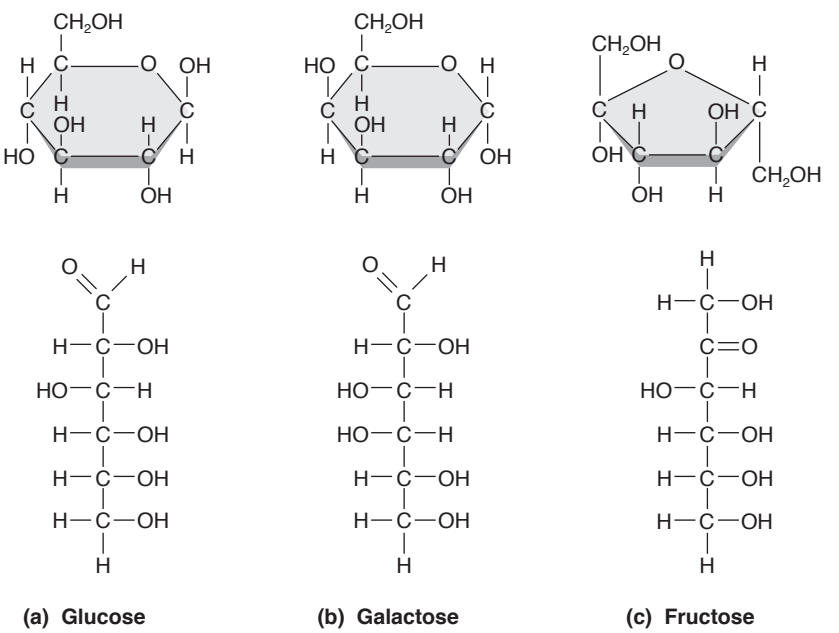

Figure 2.1 Chemical structure of the three monosaccharides depicted in both the linear and ring configurations

two). Monosaccharides and disaccharides are known as simple sugars, or simple carbohydrates. The three most common monosaccharides in the diet are glucose, **fructose**, and **galactose**. Each contains 6 carbon, 12 hydrogen, and 6 oxygen atoms but differ in their arrangement (Figure 2.1). Glucose, also called dextrose or blood sugar, is produced in plants through the process of photosynthesis, which uses energy from the sun to combine carbon dioxide and water. Glucose rarely occurs as monosaccharide in food; it is most often found as part of a disaccharide or starch. The digestion of more complex carbohydrates also produces glucose, which is then absorbed across the wall of the small intestine so that it can be (1) used directly by cells for energy, (2) stored as glycogen in muscle and liver, or (3) converted into fat. Inside of the body, glucose can be formed from the breakdown of stored carbohydrate (i.e., glycogen), or synthesized from carbon skeletons of specific amino acids, glycerol, pyruvate, and lactate.

Fructose, also called fruit sugar, is another common monosaccharide. It tastes sweeter than glucose. It is found naturally in fruits and vegetables mostly as a part of sucrose, a disaccharide, and make up more than half of the sugar in honey. It accounts for about 10 percent of the average energy intake in the United States. The small intestine absorbs some fructose directly into the blood. It is then transported to the liver where it is quickly metabolized. Much is converted into glucose, but the rest goes on to form other compounds, such as fat, if fructose is consumed in very high amounts. Most of the free fructose in our diets comes from the use of high-fructose corn syrup in soft drinks, candies, jams, jelly, and many other fruit products and desserts.

Galactose occurs most often as a part of lactose, the disaccharide in milk, and is rarely present as a monosaccharide in the food supply. After lactose is digested and absorbed, galactose arrives in the liver. There it is either transformed into glucose or further metabolized into glycogen.

Disaccharides

The combination of two monosaccharides yields a disaccharide. The disaccharides (double sugars) include **sucrose** (cane sugar or table sugar), **maltose** (malt sugar), and **lactose** (milk sugar). Sucrose forms when the two sugars glucose and fructose bond together (Figure 2.2). Sucrose is found naturally in sugarcane, sugar beets, honey, and maple sugar. These products are processed to varying degrees to make brown, white, and powdered sugars. Animals do not produce sucrose or much of any carbohydrate except for glycogen. Sucrose is considered to be the most common dietary disaccharide and constitutes up to 25 percent of the total caloric intake in the United States.

Maltose is a disaccharide consisting of two molecules of glucose (Figure 2.2). This sugar is made whenever starch breaks down, as happens in plants when seeds germinate and in human beings during carbohydrate digestion. For example, this sugar is responsible for the slightly sweet taste experienced when bread is held in the mouth for a few minutes. As salivary **amylase** begins digesting the starch, some sweeter-tasting maltose is formed. Maltose plays an important role in the beer and liquor industry. In the production of alcoholic beverages, starches in various cereal grains are first converted into simpler carbohydrates. The products of this step – maltose, glucose, and other sugars – are then mixed with yeast cells in the absence of oxygen. The yeast cells convert most sugars into alcohol or ethanol and carbon dioxide, a process called **fermentation**.

Lactose forms when glucose bonds with galactose during the synthesis of milk (Figure 2.2). Lactose is the only sugar found naturally in animal foods. Depending on milk's fat content, lactose contributes 30 to 50 percent of the energy in milks. As the least sweet of the disaccharides, lactose can be artificially processed and is often present in carbohydrate-rich, high-calorie liquid meals. A substantial segment of the world's

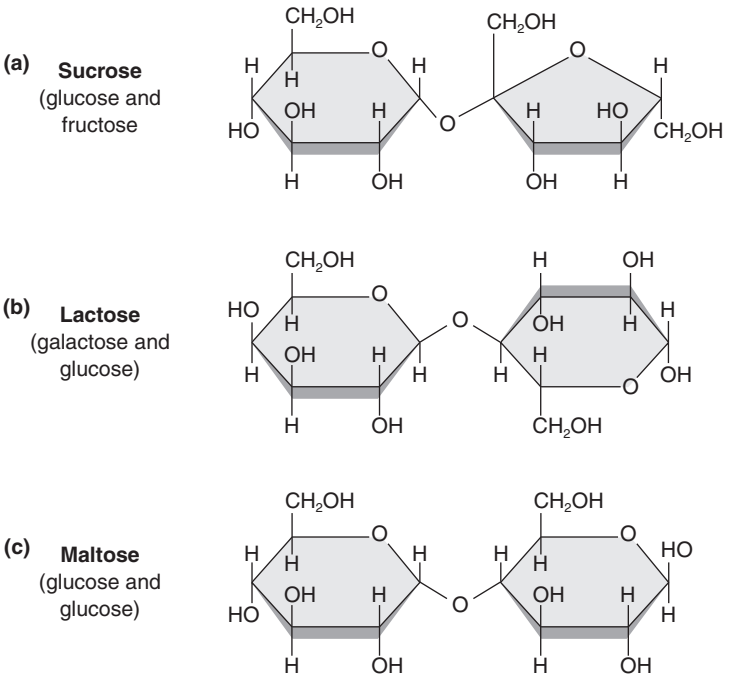

Figure 2.2 Chemical structure of the three disaccharides depicted in the ring configurations

population is lactose intolerant; these individuals lack adequate quantities of the enzyme **lactase** that splits lactose into glucose and galactose during digestion.

Complex carbohydrates

Complex carbohydrates are made up of many monosaccharides linked together in chains (Figure 2.3). They are generally not sweet to the taste like simple carbohydrates. Short chains of three to ten monosaccharides are called oligosaccharides and chains that contain more than ten monosaccharides are called polysaccharides. Oligosaccharides such as raffinose and stachyose are found in beans, cabbage, Brussels sprouts, broccoli, asparagus, other vegetables, and wholegrains. These cannot be digested by enzymes in the human stomach and small intestine, so they pass undigested into the large intestine. Here bacteria digest them, producing gas and other by-products, which can cause abdominal discomfort and flatulence. Over-the-counter enzyme tablets and solutions, such as Bean-O, can be consumed to break down oligosaccharides before they reach the intestinal bacteria, thereby reducing the amount of gas produced.

Starch

The term polysaccharide refers to the linkage of ten to thousands of monosaccharide residues by glycosidic bonds. Polysaccharides are classified into plant and animal categories. Polysaccharides stored in plants are mainly referred to as **starch**, a long, branched or unbranched chain of hundreds or thousands of glucose molecules linked together. These giant starch molecules are packed side by side in grains such as in wheat

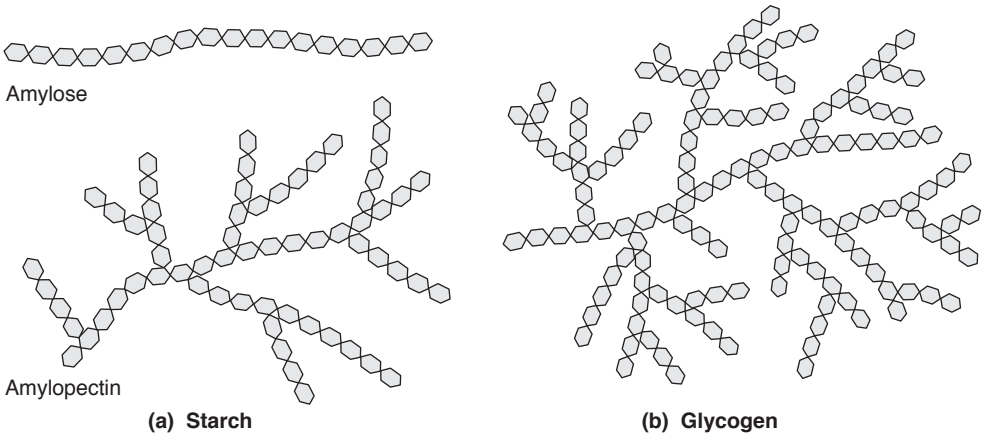

Figure 2.3 Comparison of some common starches and glycogen

or rice, in root crops and tubers such as yams and potatoes, and in legumes such as peas and beans. When you eat the plant, your body hydrolyzes the starch to glucose and uses the glucose as an energy source. All starchy foods come from plants. Grains are the richest food sources of starch, providing much of food energy all over the world – rice in Asia; wheat in Canada, the United States, and Europe; corn in much of Central and South America; and millet, rye, barley, and oats elsewhere.

There are two forms of starch digestible by humans: **amylose** and **amylopectin** (Figure 2.3). Amylose, a long, straight chain of glucose units, comprises about 20 percent of the digestible starches found in vegetables, beans, breads, pasta, and rice. Amylopectin is a highly branched chain and makes up the remaining 80 percent of digestible starches in the diet. The relative proportion of each starch form determines the digestibility of a food containing starch. The enzymes that break down starches into glucose and other related sugars act only at the end of a glucose chain. Amylopectin, because it is branched, provides many more ends for enzyme action. Therefore, amylopectin is digested more rapidly and raises blood glucose much more readily than amylose. **Cellulose** is another form of polysaccharide found in plants. Although similar to amylose, it cannot be digested by human enzymes.

Fiber

Fiber as a class is mostly made up of polysaccharides, but they differ from starches in that the chemical links that join the individual sugar units cannot be digested by human enzymes in the gastrointestinal tract. This prevents the small intestine from absorbing the sugars that make up the fibers. Consequently, fibers contribute little or no energy to the body. Fibers exist exclusively in plants; they make up the structure of leaves, stems, roots, seeds, and fruit covering. Fiber is not a single substance, but a group of substances including cellulose, hemicelluloses, pectins, gums, and mucilages, as well as the non-carbohydrate, lignin. In total, these constitute all the non-starch polysaccharides in foods. Nutrition facts labels generally do not list these individual forms of fiber, but instead lump them together under the term dietary fiber.

These various forms of fiber differ in many aspects, but may generally be divided into two categories: **soluble fiber** and **insoluble fiber** (Table 2.1). Some forms of fiber are

Table 2.1 Classification of fibers

Type	*Chemical components*	*Physiological effects*	*Major food sources*
Insoluble fibers	Celluloses, hemicelluloses, lignin	Increase fecal bulk, decrease intestinal transit time	Wheat bran, rye bran, wholegrains, broccoli
Soluble fibers	Pectins, gums, mucilages, some hemicelluloses	Delay stomach emptying, slow glucose absorption	Oats, apples, beans, barley, carrots, citrus fruits, seaweed

considered soluble because they can be digested by bacteria in the large intestine. These soluble fibers are found around and inside the plant cells. They include pectins, gums, mucilages, and some hemicelluloses. They can form viscous solutions when placed in water and are therefore referred to as soluble fibers. Food sources of soluble fibers include oats, apples, beans, and seaweed. Fibers that cannot be broken down by bacteria in the large intestine and do not dissolve in water are called insoluble fibers. Insoluble fibers are primarily derived from the structural parts of plants, such as cell walls, and include cellulose, some hemicelluloses, and lignin. Food sources of insoluble fiber include wheat bran and rye bran, which are mostly hemicelluloses and celluloses, and vegetables such as broccoli, which contain woody fibers comprised partly of lignin. Most foods of plant origin contain mixtures of soluble and insoluble fibers.

Glycogen

Glycogen is found to only a limited extent in meats and not at all in plants. For this reason, glycogen is not a significant food source of carbohydrate, but it does perform an important role in the body. Glycogen consists of a chain of glucose units with many branches, providing even more sites for enzyme action than amylopectin (Figure 2.3). Such a highly branched arrangement permits rapid hydrolysis or breakdown. When the hormone message "release energy" arrives at the storage sites in the liver or muscle cell, enzymes respond by attacking all the many branches of each glycogen simultaneously, thereby making a surge of glucose possible.

Glycogen is the only stored form of carbohydrates in humans. However, the amount of glycogen in the body is relatively small – about 400 to 500 grams. Glycogen is mainly stored in muscle and the liver. A well-nourished 80-kg person can store up to approximately 500 grams with 80 percent or ~400 grams of it existing as muscle glycogen. Because each gram of carbohydrate contains about 4 kcal of energy, the typical person stores between 1500 and 2000 kcal of carbohydrate energy – enough total energy to power a high-intensity 20-mile run. The amount of glycogen stored in muscle can be temporarily increased by a diet and exercise regimen called carbohydrate loading or glycogen super-compensation. This regimen is often used by endurance athletes to build up glycogen stores before an event. Extra glycogen can mean the difference between running only 20 miles and finishing a 26-mile marathon before exhaustion takes over. The details regarding how glycogen super-compensation is carried out are provided in Chapter 10.

Food sources of carbohydrates

The foods that yield the highest percentage of calories from carbohydrates are table sugar, honey, jam, jelly, and fruits. Table 2.2 lists common food sources of carbohydrates,

Table 2.2 Selected food sources of carbohydrate

Foods	*Serving size*	*Carbohydrate (g)*
Baked potato	1	51
Spaghetti noodles	1 cup	40
Cola drink	12 fluid ounces	39
M&M candies	1/2 ounce	30
Banana	1	28
Rice (cooked)	1/2 cup	22
Corn (cooked)	1/2 cup	21
Low-fat yogurt	1 cup	19
Kidney beans	1/2 cup	19
Orange	1	16
Carrot (cooked)	1 cup	16
Wholewheat bread	1 slice	16
Oatmeal	1/2 cup	13
1% milk	1 cup	13
Kiwi	1	11
Pineapple chunks	1/2 cup	10
Broccoli	1 cup	7
Peanut butter	2 tablespoon	7
Peanuts	1 ounce	6
Tofu	1 cup	4

among which cornflakes, rice, bread, and noodles all contain at least 75 percent of calories as carbohydrate. Foods with moderate amounts of carbohydrate calories are peas, broccoli, oatmeal, dry beans and other legumes, cream pies, French fries, and fat-free milk. In these foods, carbohydrate content is diluted either by protein or by fat. Foods with essentially no carbohydrates include beef, eggs, poultry, fish, vegetable oils, butter, and margarine.

It is recommended that adults consume 14 grams of dietary fiber per 1000 kcal. However, the average daily intake of fiber in the United States is about half this amount (Lang and Jebb 2003). There are many ways to ensure adequate fiber intake. Wholegrains and cereals, legumes, fruits, and vegetables are probably the best options. It is important to select foods made with wholegrains. Nutritionally, white bread, white rice, and white pasta are no match for their whole-grain counterparts. This is because the nutritional value of wholegrain is greatest when all three layers of wheat kernel, namely bran, germ, and endosperm, are intact. Generally speaking, coats of grains and legumes and the skins and peel of fruits and vegetables contain relatively high fiber content. Milling removes the bran and germ layers, resulting in finely ground, refined flour. To restore some of the lost nutrients, food manufacturers fortify their products with a variety of vitamins and minerals. However, many other important nutrients lost during processing are not replaced. The fiber contents of selected foods are shown in Table 2.3.

Both monosaccharides and disaccharides are collectively regarded as sugars. Sugars may also be divided into added sugars and naturally occurring sugars. Added sugars are not nutritionally and chemically different from sugars occurring naturally in foods. The only difference is that they have been refined and thus separated from their plant sources, such as sugarcane and sugar beets. Foods in which naturally occurring sugar predominate, such as milk, fruits, and vegetables, provide not only energy but also fiber and micronutrients. In contrast, foods with large amounts of added sugars, such as soft drinks, cakes, cookies, and candy, often have little nutritional value beyond the calories they contain. For example, a tablespoon of sugar contains 50 kilocalories but almost no

Table 2.3 The dietary fiber content in selected common foods

Foods	*Serving size*	*Fiber (g)*
Fruits		
Raspberries	1 cup	8.0
Pear, with skin	1 medium	5.5
Apple, with skin	1 medium	4.4
Strawberries (halves)	1 1/4 cups	3.8
Banana	1 medium	3.1
Orange	1 medium	3.1
Raisins	2 tablespoons	1.0
Grains, cereals, and pasta		
Spaghetti, wholewheat, cooked	1 cup	6.2
Barley, pearled, cooked	1 cup	6.0
Bran flakes	3/4 cup	5.3
Oat bran muffin	1 medium	5.2
Oatmeal, quick, regular, or instant, cooked	1 cup	4.0
Popcorn, air-popped	3 cups	3.5
Brown rice, cooked	1 cup	3.5
Bread, rye	1 slice	1.9
Bread, wholewheat or multigrain	1 slice	1.9
Legumes, nuts, and seeds		
Split peas, cooked	1 cup	16.3
Lentils, cooked	1 cup	15.6
Black beans, cooked	1 cup	15.0
Lima beans, cooked	1 cup	13.2
Baked beans, vegetarian, canned, cooked	1 cup	10.4
Almonds	1 ounce (23 nuts)	3.5
Pistachio nuts	1 ounce (49 nuts)	2.9
Pecans	1 ounce (19 halves)	2.7
Vegetables		
Peas, cooked	1 cup	8.8
Broccoli, boiled	1 cup	5.1
Turnip greens, boiled	1 cup	5.0
Sweet corn, cooked	1 cup	4.2
Brussels sprouts, cooked	1 cup	4.1
Potato, with skin, baked	1 medium	2.9
Tomato paste	1/4 cup	2.7
Carrot, raw	1 medium	1.7

Source: adapted from the data provided by Mayo Clinics.

nutrients other than sugar. A small orange also has about 50 kilocalories but contributes vitamin C, folate, potassium, some calcium as well as fiber. Foods that contain most of the added sugars in American diets are as follows:

- Regular soft drinks
- Candy
- Cakes
- Cookies
- Pies
- Fruit drinks, such as fruit juice and fruit punch
- Milk-based products, such as ice cream, sweetened yogurt, and sweetened milk
- Grain products, such as sweet rolls and cinnamon toast.

Major roles of carbohydrates in the body

The major function of carbohydrates in the body is to provide energy, especially during high-intensity exercise. Energy derived from blood-borne glucose and the breakdown of muscle and liver glycogen ultimately powers contractile processes of skeletal, cardiac, and smooth muscle tissues. Some of the energy is also used for many other biological processes, such as digestion and absorption, glandular secretion, metabolic reactions, and homeostatic regulations.

Storing glucose as glycogen

After a meal, monosaccharides are absorbed and travel via the hepatic portal vein to the liver where much of the fructose and galactose is metabolized for energy. The fate of the absorbed glucose depends on the energy needs of the body. If glucose is needed for the tissues, it is transported in the blood, reaching cells throughout the body. The amount of glucose in the blood is regulated at about 70 to 100 mg per 100 ml of blood. This ensures adequate glucose delivery to body cells, which is particularly important for brain and red blood cells that rely almost exclusively on glucose as an energy source. If blood glucose levels rise too high, the secretion of insulin from the pancreas is increased. This will then cause liver cells to link the excess glucose molecules by condensation reaction into long, branched chains of glycogen. When blood glucose levels fall below the normal range, secretion of glucagon from the pancreas increases, and as a result the liver cells dismantle the glycogen by hydrolysis reactions into single molecules of glucose and release them into the bloodstream. Thus, glucose becomes available to supply energy to the brain and other tissues, regardless of whether the person has eaten recently. Muscle cells can also store glucose as glycogen, as mentioned earlier, but they keep most of their supply, using it just for themselves during exercise. Glycogen holds water and thus is rather bulky. This is why the body can only store enough glycogen to provide energy for relatively short periods of time – less than a day during rest and a few hours at most during exercise. For its long-term energy reserves or for use over days or weeks of food deprivation, the body uses its abundant, water-free fuel: fat.

Using carbohydrates as energy

The main function of carbohydrates is to supply calories for use by the body. Certain tissues in the body, such as red blood cells, can use only glucose as fuel. Most parts of the brain and central nervous system also derive energy only from glucose unless the diet contains almost none. In that case, much of the brain can use partial breakdown products of fat called ketone bodies for energy needs. Other body cells, including muscle cells, can use carbohydrates as a fuel but they can also use fat or protein for energy needs. Glucose fuels the work of most body cells. Inside a cell, glucose is metabolized through cellular respiration to produce carbon dioxide, water, and energy in the form of ATP. Providing energy through cellular respiration involves several interconnected chemical pathways that take place primarily in mitochondria. As mentioned earlier, liver cells store glucose in the form of glycogen as a reserve. However, the total glycogen stores in the liver last only for hours. To keep providing glucose to meet the body's energy needs, a person has to consume dietary carbohydrate frequently. Those who fail to meet their carbohydrate requirements may draw energy from the other two energy-yielding nutrients, namely fat and protein. Nevertheless, their level of performance during vigorous exercise may reduce significantly.

Sparing protein from use as an energy source

A diet that supplies enough digestible carbohydrates to prevent the breakdown of proteins for energy needs is considered protein sparing. Under normal circumstances, of digestible carbohydrates in the diet most end up as blood glucose, and protein is reserved for functions such as building and maintaining muscles and vital organs. However, if you don't eat enough carbohydrates, your body is forced to make glucose from body protein. This process of producing new glucose using non-glucose molecules such as amino acids is called **gluconeogenesis**. The gluconeogenesis occurs in the liver and kidney cells and is stimulated by the hormone glucagon secreted from the pancreas in response to a decreased blood glucose concentration. Newly synthesized glucose is released into the blood to prevent blood glucose from dropping below the normal range. However, such a process of gluconeogenesis, if continued, can drain the pool of amino acids available in cells for other crucial functions. During long-term starvation, the continuous withdrawal of protein from the muscles, heart, liver, kidney, and other vital organs may result in weakness, poor function, and even failure of the body system. Gluconeogenesis can also be stimulated by the hormone cortisol. This hormone responds to dangerous or stressful situations by causing a rapid release of glucose into the blood to meet energy needs.

Carbohydrates are needed to break down fat

In addition to the loss of protein, insufficient carbohydrate intake can also affect fat metabolism. To metabolize fat completely, a small amount of carbohydrates must be available. This is because acetyl-CoA, produced from fat breakdown, may be used to produce energy via the Krebs cycle only if it can combine with a four-carbon oxaloacetate molecule derived from carbohydrate metabolism. When carbohydrates are in short supply, oxaloacetate is limited and acetyl CoA cannot be metabolized to carbon dioxide and water. Instead, liver cells convert acetyl-CoA into compounds known as ketones or ketone bodies (Figure 2.4). Ketone production is a normal response to limitations of glucose transport into the cell such as in diabetes or glycogen depletion through starvation, a very low carbohydrate diet, or prolonged exercise. Ketones can be used for

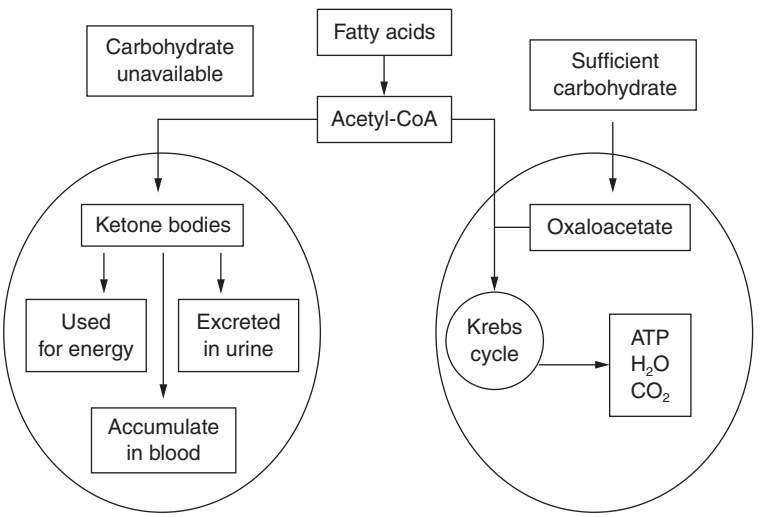

Figure 2.4 The availability of carbohydrate determines how fatty acids are metabolized

energy by tissues, such as those in the heart, muscle, and kidney. Even the brain, which requires glucose, can adapt to obtain a proportion of its energy from ketones. Excess ketones are excreted by the kidney in urine. However, if excretion is outpaced by production, or fluid intake is too low to produce enough urine to excrete ketones, ketones can build up in the blood, causing ketosis. Mild ketosis, which occurs with moderate caloric restriction such as during a weight loss diet, produces symptoms including headache, a dry mouth, foul-smelling breath, and, in some cases, a reduction in appetite. High ketone levels, if left untreated, will increase the acidity of the blood and may result in coma and death.

Glycemic response

Our bodies react differently to different sources of carbohydrates. For example, a serving of a high-fiber food, such as baked beans, results in lower blood glucose levels compared to the same serving size of mashed potatoes. How quickly blood glucose levels rise after a meal is affected by the composition of the food or meal. Fat and protein consumed with high-carbohydrate foods cause the stomach to empty more slowly and therefore delay the rate at which glucose enters the small intestine where it is absorbed. This will then cause a slower rise in blood glucose. Fiber also slows the rise in blood glucose because fiber, due to its unique structure, takes longer to be digested. In contrast, drinking a sugar-sweetened soft drink on an empty stomach will cause blood glucose to increase rapidly. As for a meal we consume daily, the glycemic responses can vary depending upon its nutrient composition. For example, for a meal mixed with chicken, rice, and green beans, which contains starch, fat, protein, and fiber, it will take at least 30 minutes before blood glucose begins to rise. However, blood glucose will rise much more quickly if we consume a meal consisting of primarily carbohydrates, such as spaghetti or white bread.

Two food measurements have been developed to predict the blood glucose response to various foods and to plan a diet to avoid hyperglycemia. The first of these tools is **glycemic index** (GI). Glycemic index is the ratio of the blood glucose response to a given food compared to a standard or reference food (typically, glucose or while bread). It is a numerical system of measuring how quickly and how high ingesting a carbohydrate food triggers a rise in circulating blood glucose. Keep in mind, however, that one person's glycemic response to a given food may be very different from someone else's. Moreover, people do not normally consume carbohydrate foods by themselves, but often with other foods containing fat and protein, such as a hamburger on a bun. Indeed, glycemic index can be influenced by many factors, including rate of ingestion, fiber content, fat and protein content, starch characteristics, food form, gastric emptying, and gastrointestinal digestion and absorption. For example, mashed potatoes are associated with higher glycemic index due to higher amylopectin content and greater surface area exposed. On the other hand, fructose has a low glycemic response mainly because of its slower absorption rate. In fact, this is one of the reasons why fructose has been recommended for use as a carbohydrate supplement prior to an athletic event. A fast rise in blood glucose can create an insulin response and the potential reactive hypoglycemia, which is detrimental to performance.

Another shortcoming of glycemic index is that it does not account for the amount of carbohydrate found in a typical serving size. Rather, it is based on blood glucose response to consuming 50 grams of carbohydrates in a given food. For example, to consume 50 grams of carbohydrates from carrots, a person would need to eat more than a pound, whereas a cup of rice (about 8 ounces) provides approximately 42 grams of carbohydrates. Therefore, another measure used to assess the effect of food on blood glucose response is the glycemic load (GL). The glycemic load may be a more useful measure, because it takes into account the glycemic index of a food as well as the amount of carbohydrate typically

found in a single serving of the food. To calculate the glycemic load of a food, the amount (in grams) of carbohydrate in a serving of the food is multiplied by the glycemic index of that food, and then divided by 100. For example, vanilla wafers have a glycemic index of 77, and a small serving contains 15 grams of carbohydrate. Hence, its glycemic load is (glycemic index × grams of carbohydrate) ÷ 100 = (77 × 15) ÷ 100 = 12. Even though the glycemic index of vanilla wafers is considered high, the glycemic load calculation shows that the impact of this food upon blood glucose levels is relatively low. Table 2.4 lists glycemic index and glycemic load values of commonly consumed foods (Foster-Powell *et al.* 2002).

Maintaining glucose homeostasis

Every body cell depends on glucose for its fuel to some extent, and cells of the brain and the rest of the nervous system depend almost exclusively on glucose for their energy. The activities of these cells never cease, and they do not have the ability to store glucose. Day and night they continually draw upon the supply of glucose in the fluid surrounding them. To maintain the supply, a steady stream of blood moves past these cells bringing more glucose from either the intestines (food) or the liver (via glycogen breakdown or glucose synthesis). To function optimally, the body must maintain blood glucose within limits that permit the cells to nourish themselves. If blood glucose falls below normal, the person may become lightheaded and fatigued, which could be fatal if left untreated.

Blood glucose homeostasis is regulated primarily by two hormones: **insulin**, which moves glucose from the blood to the cells, and **glucagon**, which brings glucose out of storage when necessary. Figure 2.5 depicts how these hormones work. After a meal, as blood glucose rises, special cells of the pancreas respond by secreting insulin into the blood. As the circulating insulin contacts the receptors of the body's other cells, the receptors respond by allowing blood glucose to enter the cells. Most of the cells take only the glucose they can use for energy right away, but the liver and muscle cells can assemble the small glucose units into long, branching chains of glycogen for storage.

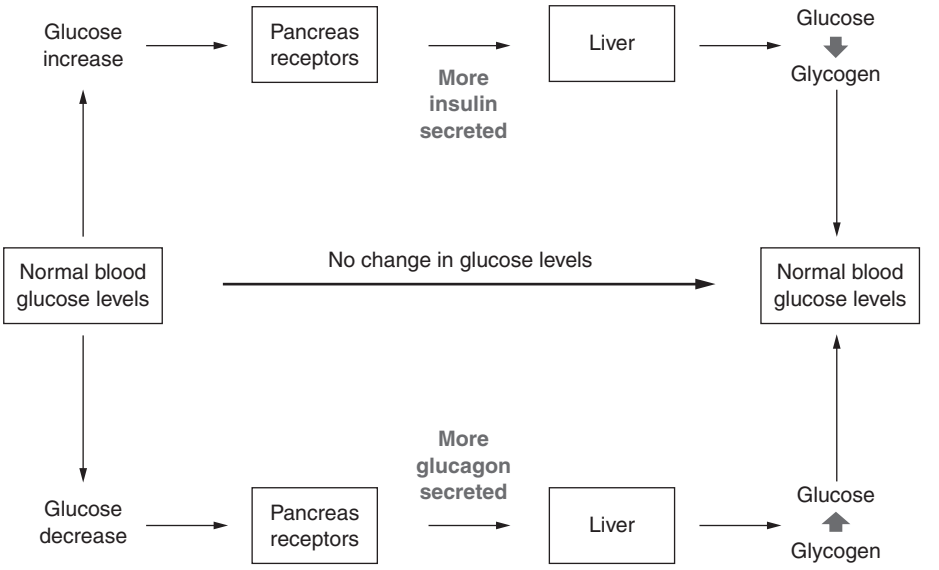

Figure 2.5 Regulation of blood glucose homeostasis by insulin and glucagon

The liver cells can also convert glucose into fat for export to other cells. As a result, elevated blood glucose returns to normal as excess glucose is stored as glycogen and fat. When blood glucose falls, as occurs between meals, other special cells of the pancreas respond by secreting glucagon into the blood. Glucagon raises blood glucose by signaling the liver to dismantle its glycogen stores and release glucose into the blood for use by all the other body cells.

Table 2.4 Glycemic Index (GI) and Glycemic Load (GL) values of common foods

Food	*Glycemic Index*[1]	*Carbohydrate/serving (g)*	*Glycemic Load*[2]
Pasta/grains			
White, long grain	56	45	25
White, short grain	72	53	38
Brown rice	45	33	16
Spaghetti	41	40	16
Bread and muffins			
Bagel	72	30	12
Pancake	67	58	39
Waffle	76	13	10
Oat bran bread	44	18	8
White bread	70	10	7
Wholewheat bread	69	13	9
Vegetables			
Boiled carrot	49	16	8
Baked potato	85	57	48
Yam	37	36	13
Corn	55	39	21
Fruits			
Apple	38	22	8
Banana	55	29	16
Orange	44	15	7
Grape	43	17	7
Plums	24	14	3
Cherries	22	12	3
Raisins	64	44	28
Raisin bran	61	19	12
Legumes			
Baked beans	48	54	26
Kidney beans	27	38	10
Navy beans	38	54	21
Dairy foods			
Milk, skim	32	12	4
Yogurt, low fat	33	17	6
Ice cream	61	31	19
Snack foods			
Potato chips	54	15	8
French fries	75	29	22
Popcorn	54	11	6

Source: adapted from Foster-Powell *et al.* (2002).

Notes
1 Low GI foods: below 55; medium GI foods: between 55 and 70; high GI foods: more than 70.
2 Low GL foods: below 15; medium GL foods: between 15 and 20; high GL foods: more than 20.

In some people, however, blood glucose regulation falls. When this happens, either of two conditions may result: diabetes or hypoglycemia. In diabetes, blood glucose surges after a meal and remains above normal levels because insulin is either inadequate or ineffective. There are two types of diabetes. In **type 1 diabetes**, the less common type, the pancreas fails to make insulin, a phenomenon believed to be caused by viruses that activate the immune system to attack and destroy cells in the pancreas as if they were foreign cells. In **type 2 diabetes**, the more common type, the cells fail to respond to insulin and this condition tends to occur as a consequence of obesity. Since the incidence of obesity has risen in recent decades, the incidence of diabetes has followed. Because obesity can precipitate type 2 diabetes, the best preventive measure is to maintain a healthy body weight.

We must be concerned with consuming foods that have a high glycemic load because these foods can elicit a large release of insulin from the pancreas. Chronically high insulin output can lead to many deleterious effects on the body: high blood triglycerides, increased fat deposition in the adipose tissue, increased fat synthesis in the liver, and a more rapid return of hunger following a meal. Over time, this increased insulin output may cause muscle to become resistant to the action of insulin, which can lead to type 2 diabetes in some people. More details on the two types of diabetes and their associated defects in metabolism can be found in Chapter 12.

In healthy people, blood glucose rises after eating and then gradually falls back into the normal range. The transition occurs without notice. In people with hypoglycemia, however, blood glucose drops dramatically, producing symptoms such as weakness, sweating, anxiety, hunger, rapid pulse, and trembling. Hypoglycemia in healthy people is rare. Most commonly, hypoglycemia occurs because of poorly managed diabetes. Too much insulin, strenuous physical activity, inadequate food intake, or illness can cause blood glucose to fall below the normal level.

Health correlates of carbohydrates

There is evidence that a high sugar intake can adversely affect blood lipid levels, thereby increasing the risk of heart disease. However, diets high in wholegrains and fibers may reduce blood cholesterol levels and thus protect against heart diseases and stroke (Kushi *et al.* 1999, Trumbo *et al.* 2002). Studies indicate that soluble fibers from foods such as legumes, oats, pectin, and flax seed are particularly effective in lowering blood cholesterol level. The cholesterol-lowering effect of increased dietary fiber has been attributed to the ability of soluble fibers to bind cholesterol and bile acids, which are made from cholesterol, in the digestive tract. When bound to fiber, cholesterol and bile acids are excreted in feces rather than being absorbed and used. The liver uses cholesterol from the blood to produce new bile acids. It has been found that the bacteria by-products of fiber fermentation in the colon also inhibit cholesterol synthesis in the liver.

High-fiber foods play a key role in reducing the risk of type 2 diabetes (Fung *et al.* 2002). As discussed in Chapter 2, a diet high in refined starches and added sugars causes greater glycemic responses and therefore increases the amount of the insulin needed to maintain normal blood glucose levels. Ample evidence exists that long-term consumption of high fibers and low sugars decreases the risk of developing type 2 diabetes (Liu *et al.* 2000, Meyer *et al.* 2000). It is believed that when viscous fibers trap nutrients and delay their digestion glucose absorption is slowed, and this helps prevent glucose surge and rebound.

To many weight loss enthusiasts, carbohydrates are viewed as the "fattening" nutrient. Indeed, studies comparing weight loss associated with a low- vs. high-carbohydrate diet

show that greater weight loss is achieved on the lower carbohydrate diet at the end of six months (Foster *et al.* 2003, Brehm *et al.* 2003). However, it should be emphasized that the weight loss associated with low carbohydrate diets is caused by a reduced caloric intake rather than by alterations in macronutrient composition of the diet. In other words, limited food choice and increased satiety associated with high-protein, high-fat foods may have caused people to eat less and therefore lose weight. There is no evidence that carbohydrate restriction causes the body to burn fat more efficiently. Although low carbohydrate diets appear effective in the short term, little, if anything, is known about their long-term effects (Astrup *et al.* 2004). Carbohydrates are no more fattening than any other energy source, and gram for gram it contains less than a half of the calories provided by fat. In fact, diets that are low in fat and protein and high in carbohydrates have long been considered effective in terms of weight loss and weight maintenance. One should strive to maintain an adequate amount of the total energy intake and to minimize the consumption of simple sugar, while maximizing the consumption of unrefined and complex carbohydrates rich in fiber. Foods rich in fiber tend to be low in fat and added sugars, and can therefore promote weight loss by delivering less energy per bite. In addition, as fibers absorb water from digestive juices, they swell, creating feeling of fullness and delaying hunger.

Carbohydrates and sports performance

Adequate bodily carbohydrate reserves are required for optimal athletic performance. As the most efficient fuel for the exercising muscles, carbohydrates are the primary source of energy during high-intensity activities. Extensive research confirms the major role carbohydrates play in endurance (aerobic) exercise as well as in strength and power events. Of a challenge, however, is that unlike protein and fat, the body has limited carbohydrate reserves. Dietary carbohydrates are stored in the body as glycogen primarily in the muscles and liver. During activity, the body relies on this stored glycogen to be released and used by the muscles and brain for energy. The body's limited glycogen stores can be depleted in a single bout of exercise of sufficient intensity and duration. Thus, daily carbohydrate intake is necessary to maintain these glycogen stores. If muscle and liver glycogen stores become depleted during exercise, the muscles will be left without fuel and fatigue will set in – a condition known as "hitting the wall."

There are other important reasons why athletes or physically active individuals should emphasize adequate carbohydrate consumption. Carbohydrates are the major fuel source for the brain and nervous system. If blood glucose and glycogen levels are low, athletes may feel irritable, tired, and lack concentration that could interfere with even simple performance-related tasks. Carbohydrates also aid in fat metabolism. The body requires the presence of carbohydrates in order to utilize fat for energy. Carbohydrates provide a "protein sparing effect," helping athletes maintain the muscle mass they worked so hard to develop. As previously mentioned, the brain requires a constant and significant amount of carbohydrates. When glycogen stores become depleted and dietary carbohydrates are not consumed, the body will turn to protein (from muscle tissue) to "make" carbohydrates in a process known as gluconeogenesis. By consuming a diet containing adequate carbohydrates and calories, the body will be less likely to have to make carbohydrates at the expense of muscle tissue.

For many athletes during intense training, multiple stressors can impair immunity and these stressors include lack of sleep, mental stress, poor nutrition, weight loss, and inflammation from exercise. Of these stressors, inadequate carbohydrate can contribute to decreased immunity and the increased possibility of getting sick. Lancaster *et al.* (2005) found that taking 30 to 60 grams of carbohydrates per hour during 2.5 hours of

high-intensity cycling prevented the decline of interferon-y, an important virus-fighting substance. Other researchers found improved levels of various antibodies when carbohydrates were taken during exercise. An adequate intake of carbohydrate can also reduce the release of hormone cortisol and free up some key amino acids to help with immune function.

Like many other people, athletes can fall prey to the latest diet and/or nutrition fad in their efforts to gain a competitive edge. Today that fad is the low carbohydrate diet as mentioned earlier. Unfortunately, a low carbohydrate diet is just the opposite of what the athlete's body needs for optimal performance. That is because carbohydrates are primary fuel for the exercising muscles and therefore essential for supporting an athlete's training and performance. Thus, a well-balanced performance diet is one that provides sufficient energy, mostly in the form of carbohydrates, with the balance of energy as proteins and fats.

Alcohol

Given the wide spectrum of alcohol use and alcohol abuse, knowledge of alcohol consumption and its relationship to overall health is essential to the study of nutrition. Alcohol is a broad term for a class of organic compounds that have common properties. For example, all alcohols have a general formula (an –OH group bonded to a carbon atom: C-OH), are quite volatile, and tend to be soluble in water. There are many different types of alcohol, and most are not safe to drink. For example, methanol, which is used to make antifreeze, can be lethal if consumed. The form of alcohol found in alcoholic beverages is a molecule called **ethanol**, which is the only type of alcohol that can be consumed and has a chemical formula of C_2H_5OH. Although alcohol is not considered a nutrient, it does provide 7 kcal per gram. An average drink, defined as about 5 fl oz of wine, 12 fl oz of beer, or 1.5 fl oz of distilled spirits, contains about 12 to 14 grams or ~0.5 oz of alcohol, which contributes about 90 kcal. The caloric contents of selected alcoholic beverages are presented in Table 2.5.

Table 2.5 Alcohol and energy content of selected alcoholic beverages

Beverages	*Typical serving (fl oz)*	*Alcohol (g)*	*Carbohydrate (g)*	*Energy (kcal)*
Beer				
Regular	12	13	13	146
Light	12	11	5	99
Wine				
Red	5	14	2.5	106
White	5	14	1.2	100
Dessert wine	5	23	17	225
Wine cooler	12	13	20	170
Distilled liquor (gin, rum, vodka, whiskey)				
80 proof	1.5	14	–	100
86 proof	1.5	15	–	105
90 proof	1.5	16	–	110
Mixed drinks				
Manhattan	3	26	3	191
Martini	3	27	–	189
Bourbon and soda	3	11	–	78
Whiskey sour cocktail	3	14	113	144

Alcohol absorption, transport, and excretion

When alcohol is consumed, it requires no digestion and is readily absorbed by simple diffusion into the blood. Although some alcohol is absorbed from the stomach, most alcohol absorption (80 percent) takes in the small intestine. Because alcohol is absorbed quickly and a relatively large amount can be absorbed directly from the stomach, the effects of alcohol consumption are almost immediate, especially if it is consumed on an empty stomach. If there is food in the stomach, absorption is slowed down because the stomach contents dilute the alcohol, reducing the amount in direct contact with the stomach wall. Food in the stomach also slows absorption because it slows stomach emptying and therefore decreases the rate at which alcohol enters the small intestine, where absorption is the most rapid.

Once absorbed, alcohol enters the bloodstream. Due to its small size and being water soluble, alcohol is rapidly distributed throughout all body water compartments. **Blood alcohol concentration** (BCA) represents the percentage of the blood that is concentrated with alcohol. For example, a person with BCA of 0.1 has one-tenth of a gram of alcohol per deciliter of blood. Within 20 minutes of consuming one standard drink (i.e., 12 oz beer, 5 oz of wine, or 1.5 oz of distilled liquor), BCA begins to rise and peaks in about 45 to 60 minutes after ingestion. A BCA of 0.02 begins to impair driving. One is legally intoxicated at a BCA of 0.08 in the USA and Canada. BCA can be influenced by many variables, including the type and quantity of alcoholic beverage consumed, the speed at which the beverage is drunk, the food consumed with it, the weight and gender of the consumer, and the activity of alcohol metabolizing enzymes.

Absorbed alcohol travels to the liver via portal circulation. In the liver, it is given metabolic priority and is therefore broken down before carbohydrate, protein, and fat. About 90 percent of the alcohol consumed is metabolized by the liver, about 5 percent is excreted into the urine, and the remainder is eliminated via the lungs during exhalation. The alcohol that reaches the kidney acts as a diuretic, increasing water excretion. Therefore, excessive alcohol consumption can cause dehydration. The amount lost via lungs is reliable enough to be used to estimate blood alcohol levels from a measure of breath alcohol.

Alcohol metabolism

Although small amounts of un-metabolized alcohol are eliminated from the body by the lungs and kidneys, the liver breaks down most alcohol. However, there is a limit to how much alcohol the liver can metabolize at any given time. The average person metabolizes 0.5 oz of pure alcohol per hour. For example, it takes about an hour to break down alcohol in a 12-oz can of beer. There are two major pathways for alcohol metabolism: **alcohol dehydrogenase (ADH) pathway** located in the cytosol of the cell and the **microsomal ethanol-oxidizing system** (**MEOS**) located in small vesicles called microsomes that form in the cell when they split off from the smooth endoplasmic reticulum.

Alcohol dehydrogenase (ADH) pathway

During light to moderate drinking, most of the alcohol is broken down via the ADH pathway. Although the liver cells have the highest levels of ADH activity, this enzyme has also been found in all parts of the intestinal tract with the greatest amounts in the stomach. In fact, the stomach begins to break down alcohol with its ADH and this action can reduce the amount of alcohol entering the body by about 20 percent. ADH converts alcohol into acetaldehyde. Acetaldehyde is a toxic compound that is further degraded

by the mitochondrial enzyme aldehyde dehydrogenase to a two-carbon molecule called acetate that forms acetyl-CoA. Although these processes produce ATP, they also slow the Krebs cycle, preventing acetyl-CoA from being further degraded. Instead, the acetyl-CoA generated by alcohol breakdown, as well as acetyl-CoA from carbohydrate and fat metabolism, is used to synthesize fatty acids that accumulate in the liver.

Microsomal ethanol-oxidizing system

Alcohol can also be metabolized in the liver by a second pathway called the microsomal ethanol-oxidizing system (MEOS). This system is particularly important when greater amounts of alcohol are consumed. It helps prevent alcohol from reaching dangerously high levels in the blood. The MEOS converts alcohol into acetaldehyde, which is then broken down by aldehyde dehydrogenase in the mitochondria. In addition to forming acetaldehyde, reactive oxygen molecules are generated, which can contribute to liver disease. The components of this secondary pathway are up-regulated in response to frequent intoxication. This is why some heavy drinkers develop a tolerance to alcohol. The MEOS also metabolizes other drugs; thus, as activity increases in response to high alcohol intake, the metabolism of other drugs may be altered.

Metabolism of alcohol is dependent on numerous factors, such as gender, race, size, physical condition, what is eaten, and the alcohol content of the beverage. The ability to produce the enzyme ADH is the key to alcohol metabolism, as it acts on about 90 percent of the dose consumed. Women absorb and metabolize alcohol differently than men. A woman cannot metabolize large amounts of alcohol in the cells lining her stomach because of low activity of ADH. While men can metabolize about 30 percent of the ingested alcohol by ADH of the stomach before it reaches the blood, women metabolize only 10 percent of ingested alcohol in this manner. Women also have less body water in which to dilute the alcohol than men. So, when a man and a woman of similar size drink equal amounts of alcohol, a larger proportion of the alcohol reaches and remains in the woman's bloodstream. Overall, women can develop alcohol-related diseases such as cirrhosis of the liver more rapidly than men with the same alcohol-consumption habits.

Benefits of moderate alcohol use

The idea of moderate alcohol use may have originated from the French paradox in the 1980s where French scientists revealed low death rates from coronary heart disease in France despite a high prevalence of smoking and high intake of dietary cholesterol and saturated fat. This paradoxical observation was initially attributed to the frequent consumption of red wine and it has been revealed by French scientists that consumption of alcohol at the level of intake in France (i.e., 20 to 30 g per day) could reduce the risk of coronary heart disease by approximately 40 percent. To date, the relationship between moderate alcohol consumption and reduced risks of cardiovascular disease has been confirmed by a vast amount of epidemiological studies. Given these studies, researchers have estimated that adults who consume an average of one to two alcoholic drinks daily have a 40 to 70 percent lower risk of cardiovascular disease than adults who do not consume alcohol or have a heavy alcohol intake (O'Keefe *et al.* 2007). **Moderate alcohol use** is defined as no more than two standard drinks per day for women and people aged over 65, and no more than three drinks per day for men. As mentioned earlier, a standard drink is defined as any drink that contains 0.5 fl oz or 14 grams of pure alcohol. This is equivalent to 12 oz of beer, 5 oz of wine, and 1.5 oz of 80 proof liquor.

You may wonder how alcohol lowers a person's risk of cardiovascular disease. Recall that cardiovascular disease results from the formation of plaque in the lining of the arteries and HDLs help protect against heart disease. Studies show that moderate daily intake of alcohol increases HDLs and may therefore offer some protection from cardiovascular disease (Rimm *et al.* 1999). There is also evidence that alcohol decreases levels of fibrinogen that promotes blood clot formation and increases levels of an enzyme that dissolves blood clots. Lower levels of fibrinogen reduce blood clots that can block blood flow to the heart, resulting in a heart attack. In addition to protecting cardiovascular health, moderate alcohol use may help guard against other age-related chronic diseases such as type 2 diabetes, gallstones, and dementia, although these potential benefits require further study.

Alcohol and athletic performance

Athletes use alcohol to enhance performance because of its psychological and physiological effects. Alcohol may be viewed as a narcotic, a depressant, that affects the brain. As a depressant of brain function, alcohol would not be advocated as a means to improve sports performance. However, although classified as a depressant, some of alcohol's effects are euphoric. Alcohol is thought to bind with receptors in the brain that may cause the release of dopamine, a neurotransmitter associated with the pleasure center of the brain and as a result normal inhibitory processes in the brain may be suppressed. For this reason, some have argued that consuming alcohol before a competition reduces tension and anxiety, enhances self-confidence, and promotes aggressiveness, and may also produce anti-tremor effects that could potentially enhance performance in sports such as rifle and pistol shooting and archery. Such an anxiolytic claim, however, has not been substantiated by research. In fact, most research indicates that alcohol precipitates undesirable side effects that impair sports performance requiring balance, eye–hand coordination, reaction time, and an overall need to process information rapidly (ACSM Position Stand 1982).

In the physiological realm, ingesting 1 g of alcohol per kilogram of body mass in one hour has been found to reduce myocardial contractility. In terms of metabolism, alcohol blunts the liver's ability to synthesize glucose from non-carbohydrate sources via gluconeogenesis. Each of these effects impairs performance in high-intensity aerobic activities that rely heavily on cardiovascular capacity and energy from carbohydrate degradation. Although alcohol contains a relatively high number of calories and its metabolic pathways in the body are short, available evidence suggests that it is not utilized to any significant extent during exercise (El-Sayed *et al.* 2005). Alcohol ingestion also increases urine output by decreasing the release of the anti-diuretic hormone. This effect could lead to dehydration and impair temperature regulation during exercise in a warm/hot environment. Starting a prolonged endurance event in a dehydrated state could certainly impair performance. Consuming alcohol post competition or training may delay the recovery process. Acting as a potent diuretic agent, alcohol consumption can hinder rehydration in recovery. Recent studies also demonstrate that ingesting alcohol at 1 to 1.5 g/kg can impair protein synthesis (Parr *et al.* 2014) and aggravates the decline in muscle performance following strenuous exercise (Barnes *et al.* 2010).

Health problems of alcohol abuse

Despite the few benefits of regular, moderate alcohol use, the risks of abuse are more numerous and harmful. When consumed in excess, alcohol is clearly hazardous to health. The consumption of alcohol has short-term effects that interfere with organ function for several hours following ingestion. It also has long-term effects that result from chronic alcohol consumption.

Short-term effects

The liver can metabolize about 0.5 oz of alcohol per hour. This is the amount of alcohol in a standard drink. When alcohol intake exceeds the ability of the liver to break it down, the excess accumulates in the blood until the liver enzymes can metabolize it. The circulating alcohol affects the brain, resulting in impaired mental and physical abilities. In the brain, alcohol acts as a depressant, slowing neurological activities. First, it affects reasoning, but, if drinking continues, this can impair vision and speech centers of the brain. Next, skeletal muscle control becomes impaired, causing lack of balance and coordination. Finally, if alcohol consumption continues, it will lead to alcohol poisoning that can slow breathing, heart rate, loss of consciousness, choking, coma, and even death.

Long-term effects

One of the complications of long-term excessive alcohol consumption is malnutrition. Alcoholic beverages contribute energy but few nutrients. As the percentage of kcal from alcohol increases, the risk of nutrient deficiencies rises. When intake of alcohol exceeds 30 percent of the total caloric intake, consumption of protein and other essential nutrients such as vitamins A and C may fall below the recommended amounts. In addition to decreasing nutrient intake, alcohol can contribute to a secondary malnutrition by interfering with nutrient absorption, even when adequate amounts of nutrients are consumed. Alcohol causes inflammation of the stomach, pancreas, and intestine, which impairs the digestion of food and the absorption of nutrients into the blood. Alcohol consumption may also be related to obesity. Calories consumed as alcohol are more likely to be deposited as fat in the abdominal region and excess abdominal fat increases the risk of high blood pressure, heart disease, and diabetes. An analysis of alcohol consumption patterns and body weight showed that individuals who consumed a small amount of alcohol frequently (one drink per day three to seven days per week) had the lowest BMI, while those who consumed large amounts infrequently had the highest BMI (Breslow and Smothers 2005).

Long-term alcohol abuse causes fatty liver, inflammation of the liver, and eventually cirrhosis. **Cirrhosis** is a progressive disease characterized by fatty infiltration of the liver. The disease usually progresses in several phases. The first phase is fatty liver, a condition that occurs when alcohol consumption increases the synthesis and deposition of fat in the liver. The second phase, alcoholic hepatitis, is an inflammation of the liver. Both conditions are reversible if alcohol consumption is stopped and good nutritional and health practices are followed. If alcohol abuse continues, cirrhosis may develop. This is an irreversible condition in which fibrous deposits scar the liver and interfere with its function. Because the liver is the primary site of many metabolic reactions, cirrhosis is often fatal.

Heavy drinking is also associated with certain types of cancer. Oral, esophageal, laryngeal, and pharyngeal cancers are more common in alcohol users than in non-alcohol users. Smokers who are also heavy drinkers are at a significantly higher risk of developing these cancers. Alcohol is also a major cause of liver cancer. By altering the liver's ability to metabolize some cancer-promoting substances such as carcinogens into harmless compounds or to disable certain existing carcinogens, alcohol's effect may influence not only liver cancer but other cancers as well. Other cancers that have been linked to alcohol overuse include breast, colon, and pancreatic cancers, although more studies are needed to reveal the underlying causes.

Summary

- Carbohydrates are chemical compounds that contain carbon, hydrogen, and oxygen, with hydrogen and oxygen in the ratio of 2:1. Simple carbohydrates include monosaccharides and disaccharides, while complex carbohydrates include oligosaccharides and polysaccharides.
- The common monosaccharides in foods are glucose, fructose, and galactose. Once they are absorbed from the small intestine and delivered to the liver, much of the fructose and galactose is converted into glucose.
- The major disaccharides are sucrose (glucose+fructose), maltose (glucose+glucose), and lactose (glucose+galactose). When digested, they yield their component monosaccharides.
- Polysaccharides include glycogen in animals and starch and fiber in plants. Glycogen and starch can be broken down by digestive enzymes, releasing the glucose units. Fiber cannot be digested by enzymes and therefore is not absorbed by the body. Fiber benefits gastrointestinal function by increasing the ease and rate at which materials move through the gastrointestinal tract.
- The foods that yield the highest percentage of calories from carbohydrates are table sugar, honey, jam, jelly, and fruits. Other foods rich in carbohydrates include cornflakes, rice, bread, and noodles. Foods with moderate amounts of carbohydrate calories are peas, broccoli, oatmeal, dry beans and other legumes, cream pies, French fries, and fat-free milk.
- Carbohydrates provide a major source of energy, but are stored in limited quantity in the liver and muscles. They are the sole source of energy for most parts of the brain and central nervous system. Carbohydrates are also needed for burning fat as well as to protect against the breakdown of body protein.
- Blood glucose homeostasis is regulated primarily by two hormones: insulin, which moves glucose from the blood to the cells, and glucagon, which brings glucose out of storage when necessary. When blood glucose regulation falls, either of two conditions may result: diabetes or hypoglycemia.
- A strong tie exists between carbohydrates and chronic diseases. There is evidence that a high sugar intake can adversely affect blood glucose and insulin levels, thereby increasing the risk of diabetes and heart disease. However, diets high in wholegrains and fibers may reduce blood cholesterol levels and thus protect against these chronic disorders.
- Alcohol is not an essential nutrient, but does supply calories to the body. It is mainly metabolized in the liver and metabolism largely depends on alcohol dehydrogenase. Factors such as gender, race, body size, and body composition determine how a person reacts to alcohol.
- Excessive alcohol use leads to cirrhosis of the liver and increased risks for developing heart disease, hypertension, and diabetes. Alcohol abuse is also associated with an increased risk of certain types of cancer, especially those of the mouth, esophagus, colon, liver, and breast.

Case study: building a healthy base and reducing risk factors

Melissa's mother died of a heart attack at the age of 55. Melissa is worried about her own health and heart disease risk. She wants to eat a healthy diet and tries to follow the dietary guidelines. She made an appointment with her physician. She filled out a questionnaire about her medical history and lifestyle, met with a dietician to evaluate her diet, and had blood drawn for blood glucose and lipid analysis.

Melissa's diet analysis indicates that she consumes about 2000 kcal, 20 percent of which come from protein, 41 percent from fat, and 39 percent from carbohydrates. The percentages of energy from saturated fat and unsaturated fat are 17 percent and 7 percent, respectively. Her fiber intake is 19 grams per day and her cholesterol intake is 380 mg per day.

The following table provides the results of her medical history and blood analysis.

Sex	*Female*
Age	35
Family history	Mother had heart attack at age 55
Height/weight	64 in/175 lb
Blood pressure	120/70 mmHg
Smoking	No
Activity level	Sedentary
Blood glucose (fasting)	97 mg/100 ml
Blood triglycerides	185 mg/100 ml
Total cholesterol	210 mg/100 ml
LDL cholesterol	160 mg/100 ml
HDL cholesterol	34 mg/100 ml

Questions

- What is your overall impression of Melissa's diet?
- How many more grams of carbohydrates would Melissa need to meet the recommendation of 45 to 65 percent of energy from carbohydrates?
- What risk factors does Melissa have for developing cardiovascular disease?
- What dietary and lifestyle changes would you recommend to reduce her risks?

Review questions

1 Describe the structure of a monosaccharide and name the three monosaccharides that are important in nutrition.
2 Explain the differences between glucose and fructose in terms of how they are absorbed. Why does fructose have a low glycemic index?
3 Name the three disaccharides found in foods and their component monosaccharides.
4 Define the terms "glucose," "glycogen," "glycogenolysis," "glycogenesis," and "glycemic index."
5 Discuss structural and functional differences between amylose and amylopectin. Why is amylose referred to as "resistant starch?"
6 How does the body maintain its blood glucose concentration? What can happen when blood glucose concentration rises too high or falls too low?
7 What health benefits are associated with a diet high in unrefined carbohydrates such as fiber?
8 Discuss the energetic roles carbohydrates play in the body.
9 Why is alcohol considered ergogenic?
10 Discuss both the short- and long-term consequences of alcohol abuse.

Suggested reading

1 Burke LM, Collier GR, Hargreaves M (1998) Glycemic index – a new tool in sport nutrition? *International Journal of Sports Nutrition*, 8: 401–415.
The glycemic index provides a way to rank foods rich in carbohydrates according to the glucose response following their intake. This review article discusses specifically how the concept of the glycemic index may be applied to training and sports competitions.

2 Coyle EF (2000) Physical activity as a metabolic stressor. *American Journal of Clinical Nutrition*, 72(2 Suppl): 512S–5120S.
Physical activity provides stimuli that promote specific and varied adaptations according to the type, intensity, and duration of the exercise performed. This article talks about how diet or supplementation can further enhance the body's responses and adaptations to these positive stimuli.

3 Jenkins DJ, Kendall CW, Augustin LS, Franceschi S, Hamidi M, Marchie A, Jenkins AL, Axelsen M (2002) Glycemic index: overview of implications in health and disease. *American Journal of Clinical Nutrition*, 76: 266S–2773S.
This article provides a solid review of literature on the glycemic index and its relevance to those chronic Western diseases associated with central obesity and insulin resistance. The authors believe that the glycemic index concept is an extension of the fiber hypothesis, suggesting that fiber consumption reduces the rate of nutrient influx from the gut.

Glossary

Alcohol dehydrogenase pathway a pathway that degrades most of the alcohol in the body.

Amylase an enzyme that breaks down starch during digestion.

Amylopectin a highly branched chain of glucose units that makes up the remaining 80 percent of the digestible starches.

Amylose a long, straight chain of glucose units that makes up about 20 percent of the digestible starches.

Blood alcohol concentration a measure that represents the percentage of the blood that is concentrated with alcohol.

Cellulose a form of polysaccharide found in plants and cannot be digested by human enzymes.

Cirrhosis a progressive disease characterized by fatty infiltration of the liver.

Disaccharides the combination of two monosaccharides and also referred to as double sugar.

Ethanol the only type of alcohol that can be consumed.

Fermentation A process during which the yeast cells convert sugars into alcohol or ethanol and carbon dioxide.

Fiber a type of carbohydrate that the body cannot digest.

Fructose also called fruit sugar and a common monosaccharide.

Galactose a part of lactose, the disaccharide in milk.

Glucagon a hormone from the pancreas that brings glucose out of storage.

Gluconeogenesis the process of producing new glucose using non-glucose molecules such as amino acids.

Glucose the simplest form of carbohydrate found primarily in the blood and used by the cells for energy.

Glycemic index a numerical system of measuring how quickly and how high ingesting a carbohydrate food triggers a rise in circulating blood glucose.

Glycogen a stored form of carbohydrate found primarily in the muscles and liver.

Insoluble fiber a type of fiber that does not dissolve in water and cannot be broken down by bacteria in the large intestine.

Insulin a hormone from the pancreas that moves glucose from the blood to the cells.

Lactase an enzyme that splits lactose into glucose and galactose during digestion.

Lactose a disaccharide consisting of glucose and galactose and also referred to as milk sugar.

Maltose a disaccharide consisting of two molecules of glucose and also referred to as malt sugar.

Microsomal ethanol-oxidizing system a pathway that metabolizes alcohol in the body.

Moderate alcohol use no more than two standard drinks per day for women and people over the age of 65, and no more than three drinks per day for men.

Monosaccharides the basic unit of carbohydrate with a formula of $C_6H_{12}O_6$.

Oligosacchardies a saccharide polymer containing a small number (typically between three to ten) of component sugars.

Polysacchardies complex carbohydrates containing many sugar units linked together.

Soluble fiber a type of fiber that can form viscous solutions when placed in water and can be digested by bacteria in the large intestine.

Starch a long, branched or unbranched chain of hundreds or thousands of glucose molecules linked together.

Sucrose a disaccharide consisting of glucose and fructose and also referred to as cane sugar or table sugar.

Type 1 diabetes a condition in which the pancreas fails to make insulin.

Type 2 diabetes a condition in which cells fail to respond to insulin.

3 Macronutrients
Lipids

Contents

Key terms

- Atherosclerosis
- Fatty acids
- Lipids
- Chylomicron
- High-density lipoprotein
- Lipogenesis

- Lipolysis
- Low-density lipoprotein
- Phospholipids
- Saturated fatty acids
- Trans-fatty acids
- Unsaturated fatty acids
- Lipoprotein
- Monounsaturated fatty acids
- Polyunsaturated fatty acids
- Sterols
- Triglycerides
- Very low-density lipoprotein

Introduction

Lipids are required for every physiological system in the body and are thus essential nutrients. For many people the thought of fatty foods invokes images of unhealthy living. We often shop for "fat-free" foods and try to avoid fats altogether. Food manufacturers have even developed "fat substitutes" to replace the fats normally found in food. However, although diets high in fat can lead to health complications such as obesity and heart disease, getting enough of the right types of fat is just as essential for optimal health.

What are the right types of fat? Should we put butter or margarine on our toast? Should we use canola or corn oil in cooking? There are hundreds of oils, butters, and margarines from which to choose. Some are solid, some are liquid, some come from plants, and some come from animals. Some are said to increase your risk of heart disease while others claim to do the opposite. Recommendations for a healthy diet suggest that we consume a diet moderate in fat and low in saturated fat, trans fat, and cholesterol. In order to follow these guidelines, we must know how much and what types of fats are in the foods we choose.

Common properties and specific types

Lipid is the chemical term for what is commonly known as fats and oils. Lipids are a diverse group of chemical compounds. They share one main characteristic: they do not readily dissolve in water. For example, think of an oil-and-vinegar salad dressing. The oil is not soluble in the water-based vinegar; the two separate into distinct layers, with oil on top and vinegar on the bottom. Lipids in the diet and in our bodies provide a concentrated source of energy. Recall in Chapter 1 that each gram of fat provides 9 kcal compared with only 4 kcal per gram from carbohydrate and protein. The major lipid classes include **fatty acids**, **triglycerides**, **phospholipids**, and **sterols**. The triglycerides predominate both in foods and in the body.

Fatty acids

In the body and in foods, fatty acids are found in the main form of lipids, triglycerides. A fatty acid is basically a long chain of carbons bonded together and flanked by hydrogen (Figure 3.1). At one end of the molecule is an acid group (COOH). At the other end, which is often referred to as the omega end, is a methyl group (CH3). Most naturally occurring fatty acids contain even numbers of carbon in their chains, usually 12 to 22, although some may be as short as 4 or as long as 26 carbons. Fatty acids with fewer than 8 carbons are called short-chain fatty acids; those with 8 to 12 carbons are medium-chain fatty acids; and those with more than 12 carbons are long-chain fatty acids. The long-chain (12 to 24 carbons) fatty acids are most common in the diet and are found primarily in meat, fish, and vegetable oils, while short- or medium-chain (6 to 10 carbons) fatty acids occur mainly in dairy products. The chain length of a fatty acid affects its chemical properties and physiological functions. In general, fatty acids with a shorter chain length tend to be liquid at room temperature, less stable, and more water soluble.

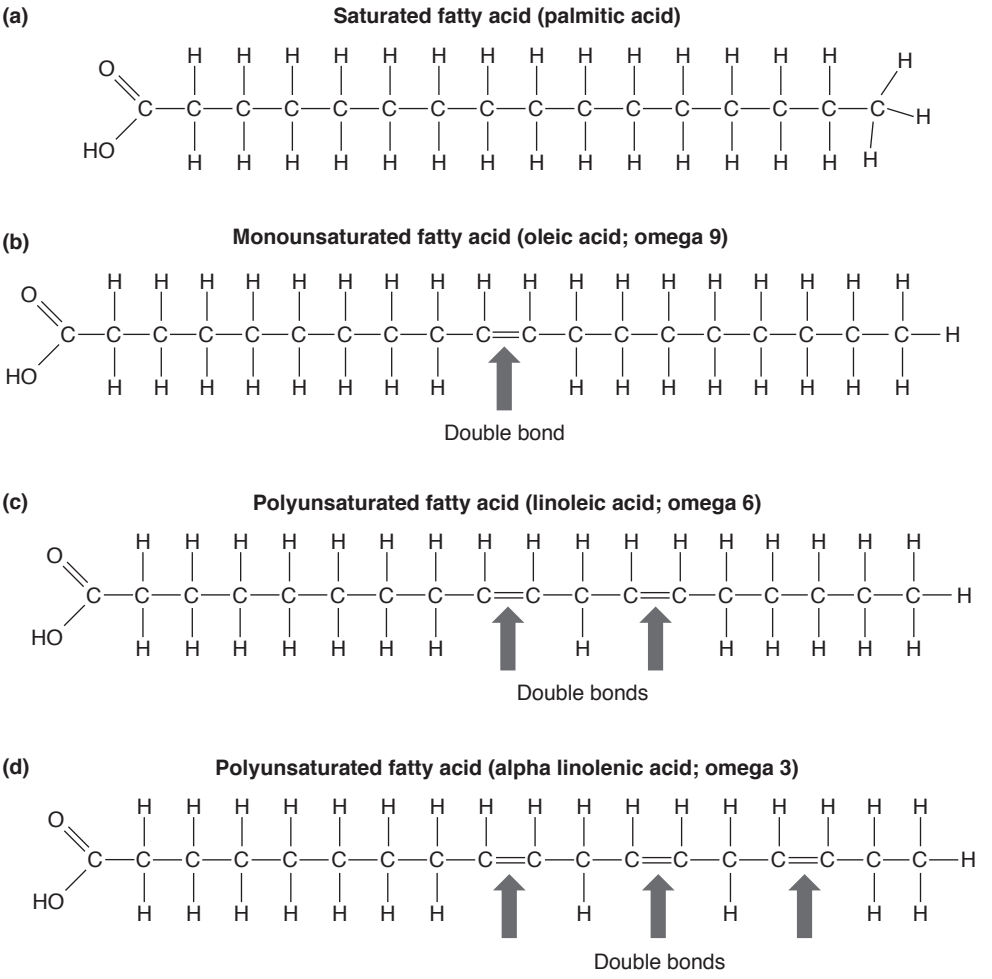

Figure 3.1 Chemical structure of saturated, monounsaturated, and polyunsaturated fatty acids. Each contains 18 carbons, but they differ from each other in the number and location of double bonds

Another way in which fatty acids differ is by the types of chemical bonds between the carbon atoms (Figure 3.1). These carbon–carbon bonds may either be single bonds or double bonds. If a fatty acid contains all single carbon–carbon bonds, it is **saturated fatty acid**. The most common saturated fatty acids are palmitic acid, which has 16 carbons, and stearic acid, which has 18 carbons. These are found most often in animal foods such as meat and dairy products. Vegetable sources of saturated fatty acids include palm oil, palm kernel oil, and coconut oil. These are often called tropical oils because they are found in plants common in tropical climates. Most fats with long-chain saturated fatty acids are solid at room temperature.

Fatty acids containing one or more double bonds are **unsaturated fatty acids** (Figure 3.1). In other words, an unsaturated fatty acid contains some carbons that are not saturated with hydrogen. More specifically, fatty acids with one double bond are **monounsaturated fatty acids**; those with two or more double bonds are **polyunsaturated fatty acids**.

In our diet, the most common monounsaturated fatty acid is oleic acid, which is prevalent in olive and canola oils. The most common polyunsaturated fatty acid is linoleic acid, found in corn, safflower, and soybean oils. Unsaturated fatty acids melt at cooler temperatures than saturated fatty acids of the same chain length. Therefore, the more unsaturated bonds a fatty acid contains, the more likely it is to be liquid at room temperature. There are different categories of unsaturated fatty acids, depending on the location of the first double bond in the chain. As shown in Figure 3.1, if the first double bond occurs between the third and fourth carbons, counting from the omega end of the chain, the fat is said to be an omega-3 (ω-3) fatty acid. Alpha-linolenic acid, found in vegetable oils, and eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), found in fish oil, are omega-3 fatty acids. If the first double bond occurs between the sixth and seventh carbons from the omega end, the fatty acid is called an omega-6 (ω-6) fatty acid. Linoleic acid, found in corn and safflower oils, is the major omega-6 fatty acid in the North American diet. Our bodies cannot synthesize double bonds in the omega-3 and omerga-6 positions. Therefore, both alpha-linolenic acid (ω-3) and linoleic acid (ω-6) are also referred to as **essential fatty acids** and they must be obtained from the diet. Omega-3 fatty acids are important for the structure and function of cell membranes, particularly in the retina of the eye and the central nervous system. Omega-6 fatty acids are important for growth, skin integrity, fertility, and maintaining red blood cell structure.

The position of the hydrogen atoms around a double bond is another way of classifying unsaturated fatty acids. Unsaturated fatty acids can exist in two different structural forms: the *cis* and *trans* forms (Figure 3.2). Most naturally occurring fatty acids are usually in the *cis* form in which the hydrogens are on the same side of the carbon–carbon double bond. During certain types of food processing, some hydrogens are transferred

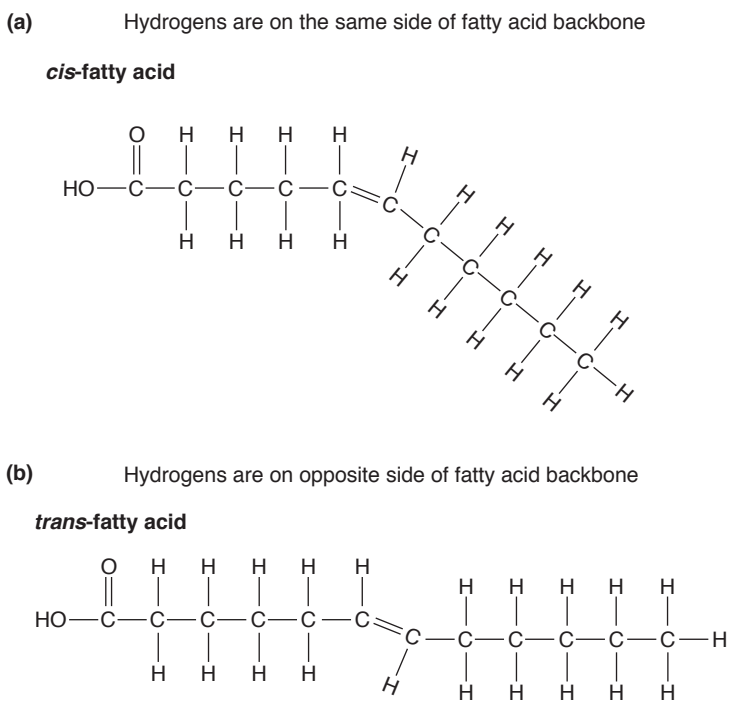

Figure 3.2 Cis- versus trans-fatty acids

to opposite sides of the carbon–carbon double bond, creating the *trans* form, or a **trans-fatty acid**. The cis bond causes the fatty acid backbone to bend. However, the *trans* bond allows the fatty acid backbone to remain straight, which makes it similar to the shape of saturated fatty acid. For this reason, trans fatty acids are also more likely to be solid at room temperature. Trans fatty acids are found in small amounts in nature and are formed during food processing involving high heat and high pressure.

Triglycerides

Most fatty acids do not exist in their free or unbound form in foods or in the body. Instead, they are part of larger, more complex molecules called triglycerides or in smaller molecules called diglycerides and monoglycerides. When three fatty acids are attached to a backbone of the three-carbon molecule glycerol, the molecule is called a triglyceride (Figure 3.3a). When one fatty acid is attached, the molecule is called a monoglyceride, and when two fatty acids are attached, it is a diglyceride. Before most dietary fats are absorbed in the small intestine, the two outer fatty acids are typically removed from triglycerides. This produces a mixture of fatty acids and monoglycerides that can be absorbed into intestine cells. After absorption, the fatty acids and monoglycerides are mostly rejoined to form triglycerides. Triglycerides may contain any combination of fatty acids: long, medium, short, saturated, or unsaturated. Triglycerides make up most of the lipids in foods and in the body, and are usually what is referred to when the term "fat" is used.

Phospholipids

Phospholipids are another class of lipids. They are important constitutes of cell membranes. Like triglycerides, they are built on a backbone of glycerol. However, at least one fatty acid is replaced with a compound containing phosphorus and often other elements such as nitrogen and choline (Figure 3.3b). Lecithin is a common example of phospholipids that is attached with a molecule of choline. The fatty acid end of phospholipids is soluble in fat or hydrophobic, whereas the phosphate end is water soluble or hydrophilic. Phospholipids are amphipathic, meaning they contain both polar (hydrophilic) and nonpolar (hydrophobic) potions. The structure allows phospholipids to be major components of cell membranes because they are able to mix with both water and fat. Having such polarized configuration makes phospholipids important in carrying out the digestion, absorption, and transport of lipids. Phospholipids are also found in food sources such as eggs, liver, soybeans, wheat germ, and peanuts.

Sterols

In addition to triglycerides and phospholipids, the lipids include the sterols, compounds with a multiple-ring structure (Figure 3.3c). A sterol can be attached to a fatty acid via an ester bond, forming a sterol ester. The most famous sterol is cholesterol. Cholesterol is a weakly polar compound. Although some free or unbound cholesterol is found in the body, most is bonded to a fatty acid. This cholesterol fatty acid is called cholesteryl ester. Cholesteryl esters are more hydrophobic than free cholesterol. Cholesterol can be manufactured by almost every tissue in the body, especially the liver. Therefore, cholesterol is regarded as a nonessential nutrient. More than 90 percent of cholesterol in the body is found in cell membranes. It is also part of myelin, the coating on many nerve cells. Cholesterol is found only in foods from animal sources. Plant foods do not contain cholesterol unless animal products are combined with them in cooking or processing.

Transporting lipids in the body

Because of the inherent difficulties related to the hydrophobic nature of lipids, the process of lipid circulation in the body is more complex than it is for other macronutrients. Generally, water-insoluble lipids are transported through the blood coated in a water-soluble envelope created when the lipids combine with phospholipids and proteins to form transport particles called **lipoproteins**. Fat-soluble vitamins are also transported in lipoproteins. Lipoproteins help transport both dietary lipids from the small intestine and stored or newly synthesized lipids from the liver.

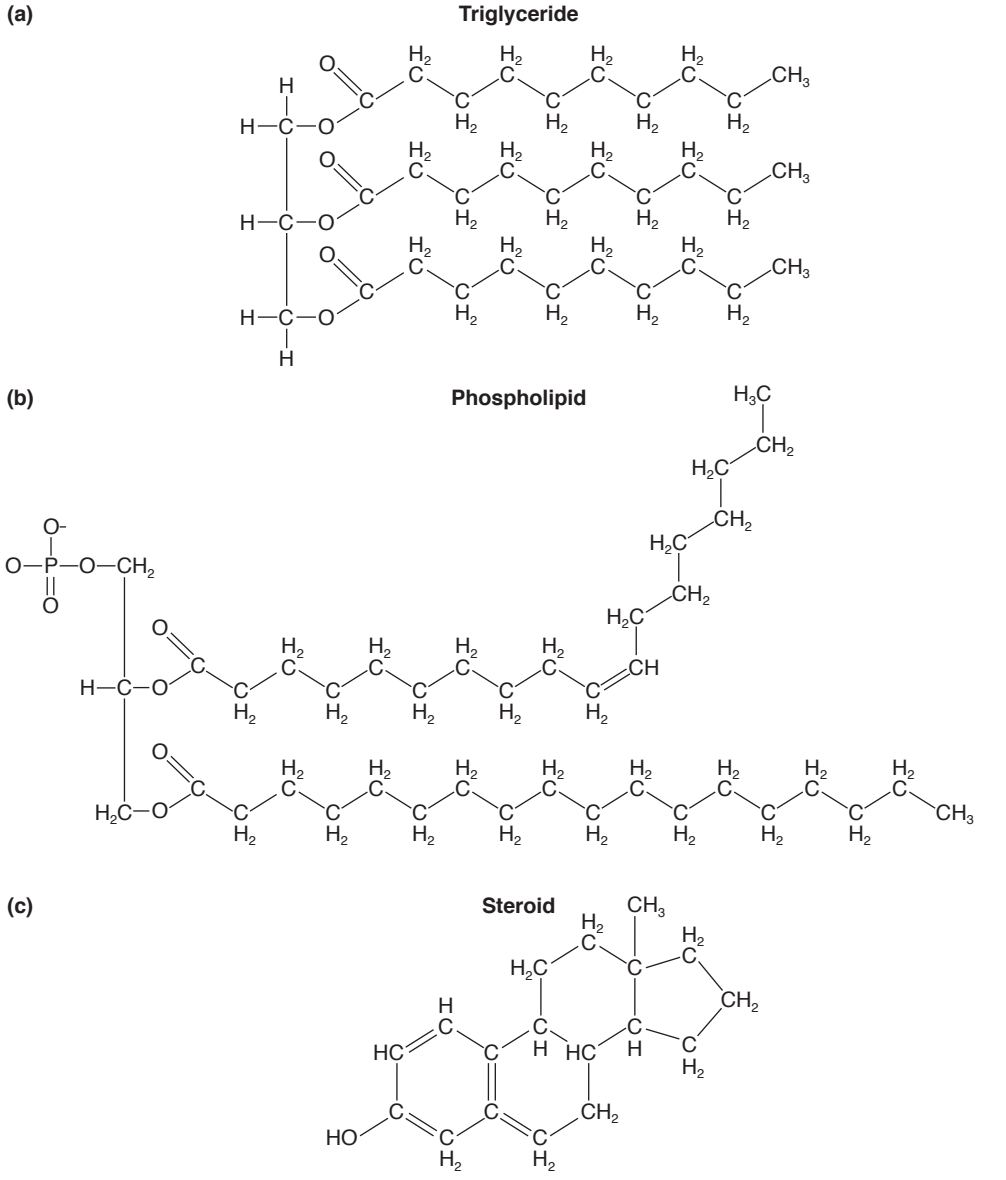

Figure 3.3 Chemical forms of common lipids: (a) triglyceride, (b) phospholipids (e.g., lecithin), and (c) sterol (e.g., cholesterol)

Transport from the small intestine

After absorption into the intestinal mucosal cells, lipids that are somewhat water soluble, such as short- and medium-chain fatty acids and phospholipids, can enter the blood. Lipids that are not soluble in water, such as long-chain fatty acids and cholesterol, cannot enter the bloodstream directly. These fatty acids are first assembled into triglycerides by the mucosal cell. These triglycerides are then combined with cholesterol, phospholipids, and a small amount of protein to form lipoproteins called **chylomicrons**. Chylomicrons are absorbed into the lymphatic system and then enter the bloodstream without first passing through the liver. As chylomicrons circulate in the blood, the enzyme lipoprotein lipase, present on the surface of the cell lining the blood vessels, breaks the triglycerides down into fatty acids and glycerol, which enter the surrounding cells. The fatty acids can be used either as fuel or resynthesized into triglycerides for storage. What remains of the chylomicrons composed mostly of cholesterol and protein goes to the liver to be disassembled.

Transport from the liver to the body cells

The liver is the major lipid-producing organ where excess protein, carbohydrate, or alcohol can be broken down and used to make triglycerides or cholesterol. Triglycerides made in the liver are incorporated into lipoprotein particles called **very low-density lipoproteins** (**VLDL**s). VLDLs are rich in triglycerides and thus are very low in density. The VLDL transports lipids out of the liver and delivers triglycerides to body cells. Once in the bloodstream, as with chylomicrons, the enzyme lipoprotein lipase breaks down the triglycerides in the VLDL so that the fatty acids can be taken up by the surrounding cells.

As its triglycerides are released, the VLDL becomes proportionately denser. Much of what eventually remains of the VLDL fraction is then called **low-density lipoproteins** (**LDLs**); these are composed primarily of the remaining cholesterol. The primary function of the LDL is to transport cholesterol to tissues. For LDLs to be taken up by the cells, a protein on the surface of the LDL particle must bind to a receptor on the cell membrane. This allows LDLs to be removed from circulation and to enter cells where their cholesterol and other components can be used. If LDLs are not readily cleared from the bloodstream, endothelial cells of the arteries will take them up, leading to **atherosclerosis**, a condition in which an artery wall thickens as the result of a build-up of fatty materials such as cholesterol. High levels of LDL in the blood have been associated with an increased risk for heart disease.

Since most body cells cannot effectively break down cholesterol, it must be returned to the liver to be eliminated from the body. This reverse cholesterol transport is accomplished by the densest of the lipoprotein particles called **high-density lipoproteins** (**HDLs**). The liver and intestine produce most of the HDLs in the blood. The HDLs pick up cholesterol from dying cells and other lipoproteins, and function as a temporary storage site for lipids. Some of the cholesterol in HDLs is taken directly to the liver for disposal, and some is transferred to organs that have a high requirement for cholesterol, such as those involved in steroid hormone synthesis. High levels of HDL in the blood are associated with a reduction in heart disease risk.

Food sources of lipids

The fat content in foods can vary from 100 percent, as found in most cooking oils and spreads such as butter, margarine, and mayonnaise, to minor trace amounts, less than 5 percent, as found in most fruits and vegetables. Some foods obviously have a high fat

content. For example, foods high in fat include nuts, bologna, avocados, and bacon, which have about 80 percent of calories as fat; these are followed by peanut butter, cheddar cheese, steak, hamburgers, ice cream, doughnuts, and whole milk (Table 3.1). However, in other foods, the fat content may be high but not as obvious. This is known as hidden fat. For example, some baked goods such as cakes, muffins, croissants, cookies, crackers, and chips contain considerable amounts of fat, but people often remain unaware of this. A 5-oz baked potato contains 145 kcal with about 3 percent fat, but people often ignore the fact that the same size serving of potato chips contains 795 kcal, over 60 percent of them from fat.

The type of fat in food is important to consider along with the total amount of fat. Animal fats are the chief contributors of saturated fatty acids. About 40 to 60 percent of the total fat in dairy and meat products is in the form of saturated fatty acids (Figure 3.4). In contrast, plant oils contain mostly unsaturated fatty acids, ranging from 70 to 95 percent of total fat. Some of the plant oils are good sources of monounsaturated fatty acids such as canola, olive, and peanut oils. Corn, sunflower, soybean, and safflower oils contain mostly polyunsaturated fatty acids. These plant oils supply the majority of the alpha-linoleic (omega-3) and linoleic (omega-6) in the North American food supply. These fatty acids are considered as essential fatty acids, meaning that they must be obtained through the diet because human cells lack the enzymes needed to produce these fatty acids. Both omega-3 and omega-6 fatty acids perform important roles in immune function and vision, help form cell membrane, and produce hormone-like compounds. Table 3.2 exhibits amounts of omega-3 fatty acid of commonly chosen fish and seafood products.

As mentioned earlier, wheat germ, peanuts, egg yolks, soybeans, and organ meats are rich sources of phospholipids. Phospholipids such as lecithin, a component of egg yolks, are often added to salad dressings. Lecithin is used as an emulsifier because of its ability to prevent mixtures of lipids and water from separating. Emulsifiers are added to salad dressings to keep the vegetable oil suspended in water. The fact that eggs are added to cake batters is another example of phospholipids being used to emulsify the fat with water.

Table 3.1 Fat content of commonly selected foods

Foods	*Serving size*	*Fat (g)*	*Calories from fat (%)*
Canola oil	1 tablespoon	14	100
Margarine	1 tablespoon	12	100
Butter	1 tablespoon	12	100
Avocado	1/2 cup	11	86
Mixed nuts	1 ounce	16	78
Peanut butter	1 tablespoon	8	76
Cheddar cheese	1 ounce	10	74
T-bone steak	3 ounces	17	66
Flax seeds	1 tablespoon	3	62
Whole milk	1 cup	8	49
Snack crackers	1 ounce	7	45
Doughnut	1	5	45
Hamburger	1	12	39
Chocolate candies	1 ounces	6	39
Chicken breast with skin	3 ounces	7	36
2% milk	1 cup	5	36
Chicken breast without skin	3 ounces	6	32
Baked beans	1/2 cup	7	31
Yogurt	8 ounces	7	28
Low-fat yogurt	8 ounces	4	18

Table 3.2 Omega-3 fatty acid content of fish and seafood

Food	*Omega-3 fatty acid (g)*
Salmon	1.15
Swordfish	1.15
Trout	1.15
Shark	0.83
Flounder	0.48
Sole	0.44
Cod	0.44
Squid	0.40
Crab	0.35
Oyster	0.30
Shrimp	0.27
Scallop	0.27
Mussel	0.26
Clam	0.26
Tuna	0.23
Lobster	0.07

Source: adapted from USDA Nutrient Data Laboratory.

Note
All values represent estimated amounts in a 3-ounce cooked portion and these values may vary markedly with species, season, diet, packaging, and cooking methods.

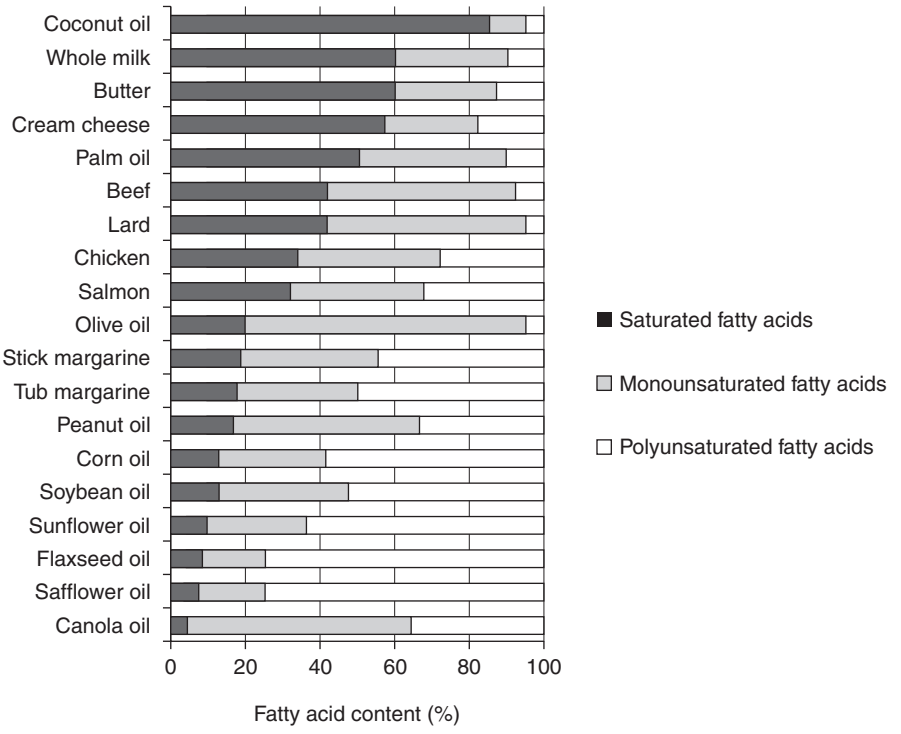

Figure 3.4 Saturated, monounsaturated, and polyunsaturated fatty acid content of various sources of dietary lipid

Cholesterol, a common example of sterol and widespread in plasma membrane of all cells, is obtained either through the diet or through cellular synthesis. Cholesterol obtained from the diet is referred to as exogenous cholesterol, while cholesterol produced within the body is referred to as endogenous cholesterol. Even if an individual maintains a "cholesterol-free" diet, endogenous cholesterol synthesis varies between 500 and 2000 mg per day. More endogenous cholesterol forms with a diet high in saturated fatty acids. Exogenous cholesterol is found only in animal foods (Table 3.3). Eggs are our main source of cholesterol, along with meat and whole milk. One egg yolk contains about 200 mg of cholesterol. Organ meats contain about 300 mg per 3-oz serving. Lean red meat and chicken contains 100 mg, whereas fish contains 50 mg in 3 oz. The production of endogenous cholesterol is usually sufficient to meet the body's needs; hence severely reducing cholesterol intake may cause little harm except in pregnant women and infants.

Major roles of lipids in the body

The blood carries lipids to various sites around the body. Once they arrive at their destinations, the lipids can get to work providing energy, insulating against temperature extremes, protecting against shock, and maintaining cellular integrity. The following sections describe each of these roles in more detail.

Table 3.3 Cholesterol content of commonly selected foods

Foods	*Serving size*	*Cholesterol content (mg)*
Skim milk	1 cup	4
Mayonnaise	1 tablespoon	10
Butter	1 pat	11
Lard	1 tablespoon	12
Cottage cheese	1/2 cup	15
Low-fat milk (2%)	1 cup	22
Half-and-half	1/4 cup	23
Hot dog	1	29
Ice cream	1/2 cup	30
Cheddar cheese	1 ounce	30
Whole milk	1 cup	34
Oyster	3 ounces	40
Salmon	3 ounces	40
Clam	3 ounces	55
Tuna	3 ounces	55
Chicken	3 ounces	70
Turkey	3 ounces	70
Beef	3 ounces	75
Pork	3 ounces	75
Lamb	3 ounces	85
Crab	3 ounces	85
Shrimp	3 ounces	110
Lobster	3 ounces	110
Heart	3 ounces	165
Egg yolk	1	210
Beef liver	3 ounces	410
Kidney	3 ounces	540

Source: USDA National Nutrient Database for Standard Reference, Release 22, 2009.

Energy source and reserves

Triglycerides provide an important source of energy. For this to happen, they must first be broken down into glycerol and fatty acids. This process, called **lipolysis**, is catalyzed by the enzyme hormone-sensitive lipase, whose activity increases when secretion of the pancreatic hormone insulin is low. Lipolysis is also stimulated by exercise and physiological stress. Compared to other energy-yielding nutrients, triglycerides represent the body's richest source of energy. As noted earlier, the complete breakdown of 1 gram of triglycerides yields approximately 9 kcal of energy, which is more than twice the yield from 1 gram of carbohydrate or protein. Therefore, gram for gram, high-fat foods contain more calories than do other foods.

The pancreatic hormone insulin stimulates the storage of triglycerides, a process that is opposite to lipolysis. This occurs during times of energy excess. Insulin causes adipocytes, and to a lesser extent skeletal muscle cells to take up glucose and fatty acids and convert glucose into fatty acids. Fatty acids are then incorporated into triglycerides. The synthesis of fatty acids and triglycerides is called **lipogenesis**. Triglycerides are stored in adipose tissue and, to a lesser extent, in skeletal muscle. Adipose tissue consists of specialized cells called adipocytes, which can accumulate large amounts of lipids. Adipose tissue is found in many parts of the body, including beneath the skin (subcutaneous adipose tissue) and around the vital organs in the abdomen (visceral adipose tissue). Considerable adipose tissue is also associated with many of the body's organs, such as the kidneys and breasts, making it possible for these organs to have ready access to fatty acids for their energy needs. Because lipids are not stored with water as are glycogen and protein, the body can store a large amount of triglycerides in a small space. This will result in our ability to warehouse almost unlimited amounts of energy. An average individual is capable of storing between 100,000 and 150,000 kcal of fat energy, which is equivalent to 75 to 100 times the carbohydrate energy that we normally store.

Insulation and protection

Triglycerides stored in adipose tissue also insulate the body and protect internal organs from injury. Although most of us do not rely on adipose tissue to keep warm, people with very little body fat can have difficulty regulating body temperature. Early research has demonstrated that fats stored just below the skin determine ability to tolerate extremes of cold exposure. For example, it was found that swimmers who excelled in swimming the English Channel showed only a slight fall in body temperature while resting in cold water and essentially no lowering effect while swimming. In contrast, body temperature of leaner, non-Channel swimmers decreased markedly under rest and exercise conditions. In fact, one common physiological response to becoming excessively lean is to develop very fine hair covering the body. This hair, often referred to as lanugo, partially makes up for the absence of subcutaneous adipose tissue by providing a layer of external insulation for the body. The presence of lanugo is common in very lean individuals, such as those with eating disorders. For large football linemen or athletes involved in contact sports, excess fat storage may provide additional cushioning to protect them from high impact. However, this protective benefit should be interpreted with caution, as such excess fat can have negative consequences for energy expenditure, thermoregulation, and exercise performance.

Components of cell membranes

Phospholipids make up the major structural component of all cell membranes. More specifically, cell membranes consist of two layers of phospholipids with the hydrophilic

polar head group pointing to the extra- and intra-cellular spaces. Remember that these compartments are predominantly water. To function effectively, cell membranes must be able to provide stable barriers between these spaces. If the cell membrane is completely hydrophilic, it will dissolve and not create a barrier. On the other hand, if the cell membrane were completely hydrophobic, there would be no communication between extra- and intra-cellular compartments. The incorporation of phospholipids that are amphipathic and have both the hydrophobic and hydrophilic portions allows cell membranes to effectively carry out their functions.

Many important body compounds are sterols. Among them are bile acids, the sex hormones such as testosterone, the adrenal hormone such as cortisol, vitamin D, and cholesterol itself. Cholesterol in the body can serve as the starting material for the synthesis of these compounds or as a structural component of cell membranes; more than 90 percent of the body's cholesterol resides in the cells. Despite popular impression to the contrary, cholesterol is a necessary compound which the body makes and uses, although cholesterol in excess can be harmful. As noted earlier, the liver is the main site where cholesterol is produced. In fact, the liver makes about 800 to 1500 mg of cholesterol per day, contributing much more to the body's total than diet. Cholesterol's harmful effects in the body occur when it forms deposits in the artery walls. These deposits may lead to atherosclerosis. If left untreated, atherosclerosis can cause heart attacks and strokes.

Health implications of lipids

Adequate amounts of essential fatty acids are required in the diet to maintain normal body function. However, diets high in fat, particularly some types of fats, are associated with an increased risk for many chronic diseases. The development of cardiovascular disease has been linked to diets high in cholesterol, saturated fat, and trans-fat (Krauss *et al.* 1996, Shikany and White 2000). In addition, the risk for certain types of cancer, including that of the breast, colon, and prostate, has been associated with a high fat intake. Obesity is also associated with diets high in fat because these diets are usually high in energy and promote the storage of body fat. Excess body fat in turn is associated with an increased risk of diabetes, cardiovascular disease, and high blood pressure.

Omega-3 fatty acids

When saturated fat in the diet is replaced by any type of polyunsaturated fat, there is a beneficial decrease in LDL cholesterol which is often regarded as "bad" cholesterol that promotes plaque build-up in the coronary arteries. One such example of polyunsaturated fat is omega-3 fatty acids. Regular consumption of omega-3 fatty acids has been found to reduce LDL cholesterol levels while possibly increasing HDL cholesterol levels (Katan *et al.* 1995, Stone 1997, Connor and Connor 1997). It has been considered that replacing some of the fat in the diet with omega-3 fatty acids reduces the incidence of cardiovascular disease (Leaf 2007, Yokoyama *et al.* 2007). This is because omega-3 fatty acids may reduce heart disease risk by preventing the growth of atherosclerotic plaque and by affecting blood clotting, blood pressure, and immune function. For example, in Mediterranean countries where the diet is high in monounsaturated fat such as olive oil as well as grains, fruits, and vegetables, the mortality rate from heart disease is only half of that in the United States according to the American Heart Association statistics. The beneficial effects are greater when the omega-3 fatty acids are consumed from seafood, such as salmon and tuna, rather than supplements. It is recommended by the American Heart Association that one should consume two 3-oz servings of fish (particularly fatty

fish such as mackerel, lake trout, herring, sardines, albacore tuna, and salmon) a week to be protected against cardiovascular diseases.

Omega-3 fatty acids also play a crucial role in brain function, as well as normal growth and development. Omega-3 fatty acids are highly concentrated in the brain and appear to be important for cognitive (brain memory and performance) and behavioral function. In fact, infants who do not get enough omega-3 fatty acids from their mothers during pregnancy are at risk for developing vision and nerve problems. Evidence is mounting to support the use of omega-3 fatty acids for treating depression, bipolar disorder, attention deficit/hyperactivity disorder (ADHD), and age-related cognitive decline.

It is important to have the proper ratio of omega-3 and omega-6 in the diet. Omega-3 fatty acids help reduce inflammation, and most omega-6 fatty acids tend to promote inflammation. The typical American diet contains 14 to 25 times more omega-6 fatty acids than omega-3 fatty acids, which many nutritionally oriented physicians consider to be way too high on the omega-6 side. In order to maintain a healthy balance in the body, a dietary ratio of omega-6 to omega-3 fatty acids of 5:1 to 10:1 is recommended. Studies suggest that higher dietary omega-6 to omega-3 ratios appear to be associated with worsening inflammation over time and a higher risk of death among hemodialysis patients (Noori *et al.* 2011).

Trans fat

Both clinical and epidemiological studies provide evidence that a high trans-fatty acid intake increases the risk of heart disease. Many studies have shown that people who ate more trans-fat were nearly 30 percent more likely to die from heart disease, and 21 percent were more likely to develop heart disease, compared with people who ate smaller amounts of trans-fats (Mozaffarian *et al.*, 2009). Some of the increase in risk is because trans-fatty acid intake increases LDL cholesterol levels and, at high intakes, lowers HDL cholesterol. Reports on trans-fatty acids have raised consumers' doubts about whether margarine is, after all, a better choice than butter for heart health. As indicated by the American Health Association, because butter is rich in both saturated fat and cholesterol while margarine is made from plant oil with no dietary cholesterol, margarine is still preferable to butter. In fact, soft margarine (liquid or tub) could be an even better choice because it is less hydrogenated and lower in trans-fatty acids. They do not raise blood cholesterol, as do the saturated fats of butter or the trans-fatty acids of hard (stick) margarine (Lichtenstein *et al.* 1999).

Obesity: excessive adiposity

Obesity is a medical condition in which excess body fat has accumulated to the extent that it may have an adverse effect on health, leading to reduced life expectancy and/or increased health problems. Although the etiology of obesity is complex, nutrient intake is a major contributor. As fatty acids provide more than twice as many calories per gram than carbohydrate and protein, fat intake is likely an important piece of the obesity puzzle. Regardless of cause, obesity is a major public health concern worldwide and is associated with increased risk for many diseases such as cardiovascular disease, type 2 diabetes, and some forms of cancer. It has been recommended that to reduce the risk for obesity we limit our fat consumption. In response to the obesity epidemic and consumer demand for reducing the prevalence of obesity, many food manufacturers produce low-fat and fat-free products as well as foods that contain fat substitutes. These alternative products replicate the taste, texture, and cooking properties of fat, but contribute less energy.

Cancer

Cancer is the second leading cause of death in the United States, and it is estimated that 30 to 40 percent of the cancers are directly linked to dietary choices. As with cardiovascular disease, there is a body of epidemiological evidence correlating diet and lifestyle with the incidence of cancer. For example, in populations where the diet is high in fat and low in fiber, the incidence of breast cancer is high. In populations where the typical fat intake is low, the incidence is lower and survival rate is better in patients with the disease. Epidemiology has also correlated the incidence of colon cancer with high-fat, low-fiber diets. The correlation is stronger for diets high in animal fat, especially those from red meats. The mechanism by which a high intake of dietary fat increases the incidence of various cancers is less well understood than the relationship between dietary fat and cardiovascular disease. However, dietary fat has been suggested to be both a tumor promoter and initiator.

Summary

- Lipids, like carbohydrate, contain carbon, hydrogen, and oxygen, but with a higher ratio of hydrogen to oxygen. The major lipid classes include fatty acids, triglycerides, phospholipids, and sterols, with the triglycerides predominating both in foods and in the body.
- Fatty acids consist of a carbon chain with an acid group at one end. The length of the carbon chain and the number and position of the carbon–carbon double bonds determine the characteristics of the fat. Some fatty acids, such as alpha-linolenic acid (ω-3) and linoleic acid (ω-6), are considered essential because they cannot be synthesized by the body. Most fatty acids are found as part of triglycerides.
- The liver is the major lipid-producing organ where excess protein, carbohydrate, or alcohol can be broken down and used to make triglycerides or cholesterol. The liver also takes up cholesterol via HDL for disposal, thereby reducing risk for atherosclerosis.
- Foods rich in fat include cooking oils and spreads such as butter, margarine, and mayonnaise. Nuts, bologna, avocados, and bacon are also high in fat, followed by peanut butter, cheddar cheese, steak, hamburgers, ice cream, doughnuts, and whole milk.
- Lipoproteins are particles found in the blood that combine lipids with proteins. They include sub-fractions of chylomicrons, very low-density lipoproteins, low-density lipoproteins, and high-density lipoproteins, which serve as vehicles for the transport of lipids between the small intestine, the liver, and body tissues.
- Lipids provide the largest nutrient store of potential energy for biological work. Other major functions of lipids include insulating against temperature extremes, protecting against shock, maintaining cellular integrity, and transporting the fat-soluble vitamins A, D, E, and K.
- Diets high in total fat, saturated fat, trans-fat, and cholesterol increase the risk for developing cardiovascular diseases, metabolic disorders, and certain types of cancer. However, diets high in ω-3 and ω-6 polyunsaturated fatty acids along with plant foods containing fiber, antioxidants, and photochemical protect against these chronic conditions.
- Omega-3 fatty acids play a crucial role in brain function, as well as normal growth and development. Evidence is mounting to support the use of omega-3 fatty acids for treating depression, bipolar disorder, attention deficit/hyperactivity disorder (ADHD), and age-related cognitive decline.

Case study: eating healthier fats

Thomas has a busy schedule, working full time and attending college, and has little time to cook meals at home. Currently, for breakfast and lunch he relies on things he can pick up on the way to school or between classes. He makes a quick dinner when he gets home in the evening. He is concerned about the fat in his diet and wants to know how to make healthier choices. Recently, Thomas analyzed his original diet and then modified it to try to meet the recommendations for a healthy mix of fats. Table 3.4 provides the results of dietary analysis for his original and modified diets.

Table 3.4 Results of Thomas's dietary analysis

Original diet

Food	*Size*	*Fat (g)*	*Sat (g)*	*Trans (g)*
Breakfast				
Bran muffin	1 large	6	2.6	0.5
Margarine	2 tsp	8	1.3	2
Whole milk	1 cup	8	5	0.2
Lunch				
Big Mac	1	31	12.5	1
French fries	1 med	22	5	5
Water	1 bottle	0	0	0
Snack				
Apple	1 med	0	0	0
Dinner				
Fish sticks	5	17	2.4	2
Tater tots	10	8	6	4
Coconut cookies	2	13	3.4	3.3
Total		113	38.2	18

Modified diet

Chol (mg)	*Food*	*Size*	*Fat (g)*	*Sat (g)*	*Trans (g)*	*Chol (mg)*
Breakfast						
24	Bran muffin	1 large	6	2.6	0.5	24
0	Orange	1 med	0	0	0	0
33	Skim milk	1 cup	2.6	1.6	0	10
Lunch						
80	Rice noodles	1 cup	0	0	0	0
0	Stir-fry veges w/oil	1 cup	5.3	0.8	0	0
0	Water	1 bottle	0	0	0	0
Snack						
0	Apple	1 med	0	0	0	0
Dinner						
33	Trout	3 ounces	12	1.2	0	63
0	Baked potato w/sour cream	1 med	3.2	1.7	0	10
0	Green beans	1/2 cup	0	0	0	0
	Salad w/oil	1 cup	10	1.2	0	0
	Frozen yogurt	2/3 cup	1.8	1.2	0	5
170	Total		40.9	10.3	0.5	112

Questions

- Assuming Thomas is eating 2500 kcal per day, calculate the percentage of energy from fat, saturated fat, and trans-fat in his original diet.
- How do these percentages compare to recommendations?
- What foods are the biggest contributors to his saturated fat intake? To his trans-fat intake? To his cholesterol intake?
- Assuming his caloric intake stays the same, calculate the percentage of energy from fat, saturated fat, and trans-fat in his modified diet.

Review questions

1 What is a lipid? Name three classes of lipids found in the body and provide an example for each.
2 How do phospholipids differ from triglycerides in structure? What roles do triglycerides and phospholipids play in the body?
3 Why is LDL-C considered "bad" cholesterol and HDL "good" cholesterol?
4 Describe the structure of saturated, monounsaturated, and polyunsaturated fatty acids and their effects in the body. Why are unsaturated fatty acids highly recommended?
5 Describe "cis-" and "trans-" fatty acids. Why do trans-fats pose a greater health concern? List some foods that are high in trans-fats.
6 What role does the liver play in transporting ingested lipids to body cells?
7 What are the major functions of lipids in the body?
8 What are the health benefits of omega-3 fatty acids?
9 What negative health consequences can excess adiposity cause?

Suggested reading

1 Burke LM, Collier GR, Hargreaves M (1998) Glycemic index – a new tool in sport nutrition? *International Journal of Sport Nutrition*, 8: 401–415.
The glycemic index provides a way to rank foods rich in carbohydrate according to the glucose response following their intake. This review article discusses specifically how the concept of the glycemic index may be applied to training and sports competition.
2 Coyle EF (2000) Physical activity as a metabolic stressor. *American Journal of Clinical Nutrition*, 72(2 Suppl): 512S–520S.
Physical activity provides stimuli that promote specific and varied adaptations according to the type, intensity, and duration of exercise performed. This article talks about how diet or supplementation can further enhance the body's responses and adaptations to these positive stimuli.
3 Jenkins DJ, Kendall CW, Augustin LS, Franceschi S, Hamidi M, Marchie A, Jenkins AL, Axelsen M (2002) Glycemic index: overview of implications in health and disease. *American Journal of Clinical Nutrition*, 76: 266S–2673S.
This article provides a solid review of literature on the glycemic index and its relevance to those chronic Western diseases associated with central obesity and insulin resistance. The authors believe that the glycemic index concept is an extension of the fiber hypothesis, suggesting that fiber consumption reduces the rate of nutrient influx from the gut.

Glossary

Atherosclerosis a condition in which an artery wall thickens as the result of a build-up of fatty materials such as cholesterol.
Chylomicrons lipoprotein particles that consist of triglycerides, cholesterol, phospholipids, and a small amount of protein.

Essential fatty acids the fatty acids that cannot be synthesized in the body and must be obtained from food.

Fatty acids a long chain of carbons bonded together and flanked by hydrogen with one end of the molecule being an acid group (COOH) and the other end being a methyl group (CH3).

High-density lipoproteins the densest lipoprotein particles that transport cholesterol to the liver.

Lipids a broad group of naturally occurring molecules which includes fats, waxes, sterols, and phospholipids.

Lipogenesis formation of triglycerides, a process that is opposite to lipolysis.

Lipolysis a process in which triglycerides are broken down into glycerol and fatty acids.

Lipoproteins transport particles formed by lipids combining with phospholipids and proteins.

Low-density lipoproteins lipoprotein particles composed primarily of cholesterol and responsible for transporting cholesterol to tissues.

Monounsaturated fatty acids the fatty acids that contain one double carbon–carbon bond.

Phospholipids differ from triglycerides in that at least one fatty acid is replaced with a compound containing phosphorus.

Polyunsaturated fatty acids the fatty acids that contain two or more carbon-carbon double bonds.

Saturated fatty acids the fatty acids that contain all single carbon-carbon bonds.

Sterols a group of lipids that consist of a multiple-ring structure, such as cholesterol.

Trans-fatty acids the unsaturated fatty acids formed during certain types of the food process in which some hydrogens are transferred to opposite sides of the carbon–carbon double bond that results in a straight shape.

Triglycerides molecules in which three fatty acids are attached to a backbone of the three-carbon molecule glycerol.

Unsaturated fatty acids the fatty acids that contain some carbons that are not saturated with hydrogen.

Very low-density lipoproteins lipoprotein particles rich in triglycerides and very low in density.

4 Macronutrients
Proteins

Contents

Key terms

- Complementary proteins
- Deamination
- Edema
- Incomplete proteins
- Lacto vegetarians
- Nonessential or dispensable amino acids
- Peptide bond
- Vegans
- Complete proteins
- Denaturation
- Essential or indispensable amino acids
- Lacto-ovo vegetarians
- Limiting amino acids
- Osmosis
- Transamination

Introduction

Protein is a macronutrient which is distinguished from carbohydrates and lipids by the fact that it contains the element nitrogen. It is made from amino acids that are joined together by peptide bonds. Plants combine nitrogen from the soil with carbon and other elements to form amino acids. They then link these amino acids together to make proteins. Some proteins are very simple, containing only a few amino acids, whereas others contain thousands. However, most proteins are of intermediate size, containing 250 to 300 amino acids. Protein in the diet provides the raw material to make all the various types of proteins that the body needs. Thousands of substances in the body are made of proteins. Aside from water, proteins form the major part of lean body mass, totaling about 15 to 20 percent of body weight. These body proteins provide an important structural and regulatory function. In some circumstances protein may be used for energy, providing 4 kcal per gram.

Amino acids: the building blocks of protein

The numerous proteins in the body are very chemically diverse due to which amino acids they contain and the ways they are linked together. Each different protein contains a specific number of amino acids in specific proportions that are bound together in a specific order. Although at least 100 amino acids are found in nature, the body uses only about 20 different amino acids to make its own proteins. Each amino acid consists of four common components: (1) a central carbon bonded to hydrogen, (2) an amino group ($-NH_2$) containing nitrogen, (3) a carboxylic acid group (-COOH), and (4) a unique side-chain group that varies in length and structure. Different side chains give specific properties to individual amino acids. Figure 4.1 shows a "generic" amino acid.

The side-chain groups on amino acids vary from one amino acid to the next, making proteins more complex than either carbohydrates or lipids. A polysaccharide such as starch may be several thousand units long, but every unit is a glucose molecule just like all the others. A protein, on the other hand, is made up of about 20 different amino acids, each with a different side-chain group. Each amino acid is defined by its side-chain group, which may be as simple as a single hydrogen atom or as complex as an organic ring structure. Appendix B presents the chemical structure for each of the 20 amino acids. Some side-chain groups also contain sulfur atoms. These subtle differences in the side-chain groups give each amino acid a unique chemical and physical feature. For example, some of the side-chain groups are negatively charged, some are positively charged, and some don't have a charge at all. The charges associated with side-chain groups help determine the final shape and function of the protein.

Of the 20 amino acids commonly found in protein, 9 cannot be made by the adult human body. These amino acids are called **essential or indispensable amino acids**, and

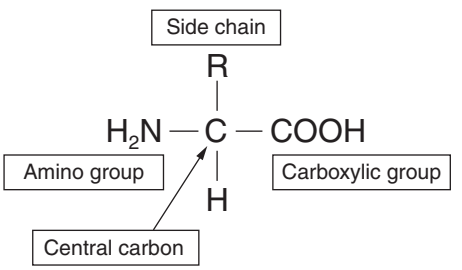

Figure 4.1 The main components of an amino acid

they must be consumed in the diet (Table 4.1). If the diet is deficient in one or more of these amino acids, new proteins containing them cannot be made without breaking down other body proteins to provide them. The 11 **nonessential or dispensable amino acids** can be made by the human body and are not required in the diet. When a nonessential amino acid needed for protein synthesis is absent from the diet, it can be made in the body. Most of the nonessential amino acids can be made by the process of **transamination** in which the amino group of one amino acid is transferred to a carbon-containing molecule to form a different amino acid.

Some amino acids are conditionally essential, meaning that they are only essential under certain conditions. For example, the conditionally essential amino acid tyrosine can be made in the body from the essential amino acid phenylalanine. If phenylalanine is in short supply, tyrosine cannot be made and becomes essential in the diet. Likewise, the amino acid cysteine is only essential when the essential amino acid methionine is in short supply. There are other factors that can influence the essentiality of amino acids. For example, some infants, especially those born prematurely, cannot make several of the nonessential amino acids such as cystine and glutamine. Thus, these amino acids must be obtained from the diet during this period of the life span. In addition, certain diseases can cause a nonessential amino acid to become essential. For example, with a genetic disorder called phenylketonuria (PKU), the body loses its ability to convert phenylalanine into tyrosine due to a lack of enzymes. Therefore, tyrosine must be supplemented via diet in patients with PKU.

Protein structure

Condensation reactions connect amino acids, just as they combine monosaccharides to form disaccharides, and fatty acids with glycerol to form triglycerides. Amino acids are linked together to form proteins by a unique type of chemical bond called a **peptide bond** (Figure 4.2). The bond is formed between the acid group of one amino acid and the nitrogen atom of the next amino acid. Two amino acids bond together to form a dipeptide. By another such reaction, a third amino acid can be added to the chain to form a tripeptide. As additional amino acids join the chain, a polypeptide is formed. Most proteins are a few dozen to several hundred amino acids long. A protein is made of one or more polypeptide chains folded into a complex three-dimensional structure.

Table 4.1 Essential and nonessential amino acids

Essential amino acids	*Nonessential amino acids*
Histidine	Alanine
Isoleucine	Arginine*
Leucine	Asparagine
Lysine	Aspartic acid
Methionine	Cysteine*
Phenylalanine	Glutamic acid
Threonine	Glutamine*
Tryptophan	Glycine*
Valine	Proline*
	Serine
	Tyrosine*

Note
* These amino acids are also classified as conditionally essential.

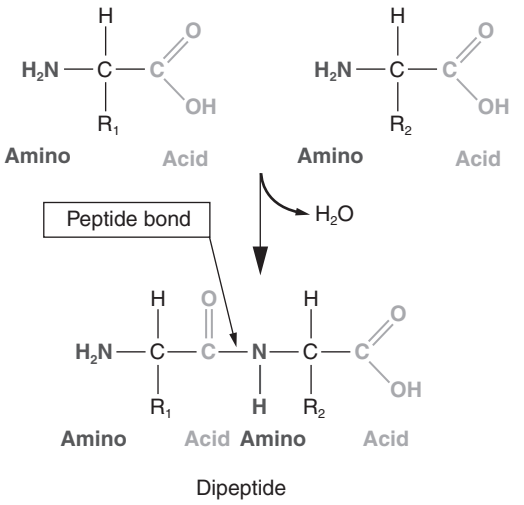

Figure 4.2 Condensation of two amino acids to form a dipeptide that contains a peptide bond

Considering the level of folding complexity of polypeptide chains, protein can be further divided into four distinct aspects: (1) primary structure, (2) secondary structure, (3) tertiary structure, and (4) quaternary structure (Figure 4.3). The primary structure concerns only the amino acid sequence of the peptide chains. The primary structure represents the basic identity of the protein. Alterations in the primary structure may be caused by inherited genetic variations. A disease called sickle cell anemia is such an example in which the shape of hemoglobin is alerted because of a genetic "error." The secondary structure of peptide chains results from weak chemic bonds, called hydrogen bonds, that twist and fold the primary structure. Such chemical interaction is due to the fact that the backbone of the peptide chain is made of amino and carboxylic acid groups with positive and negative charges. A normally functional protein always exists in a tertiary structure that is three-dimensional and contains additional folding of the peptide chain. Such additional folding is brought up by interactions between the side chains. The quaternary structure is referred to a protein that is made from more than one polypeptide chain. Hemoglobin is an example of a protein with quaternary structure and is made from four separate polypeptide chains, each of which combines with an iron-containing unit called a heme. Heme is the portion of the hemoglobin molecule that actually holds the oxygen and carbon dioxide gases as they are transported in the blood.

A protein's final shape determines its ability to carry out its function. However, there are many conditions that can alter a protein's shape. One example is **denaturation**. Denaturation occurs when a protein unfolds in unusual ways. Compounds and conditions that cause denaturation include heat, acid, detergents, base, salts, alcohol, and heavy metals such as mercury. A familiar example of protein denaturation occurs when an egg white is heated; proteins unfold, and the egg white changes from thin and clear liquid to a cloudy solid. Another example is mercury which can disrupt bonds between side chains and thus tertiary structure. Such denaturating action explains why mercury exposure can cause numbness, hearing loss, visual problems, difficulty walking, and severe emotional and cognitive impairments.

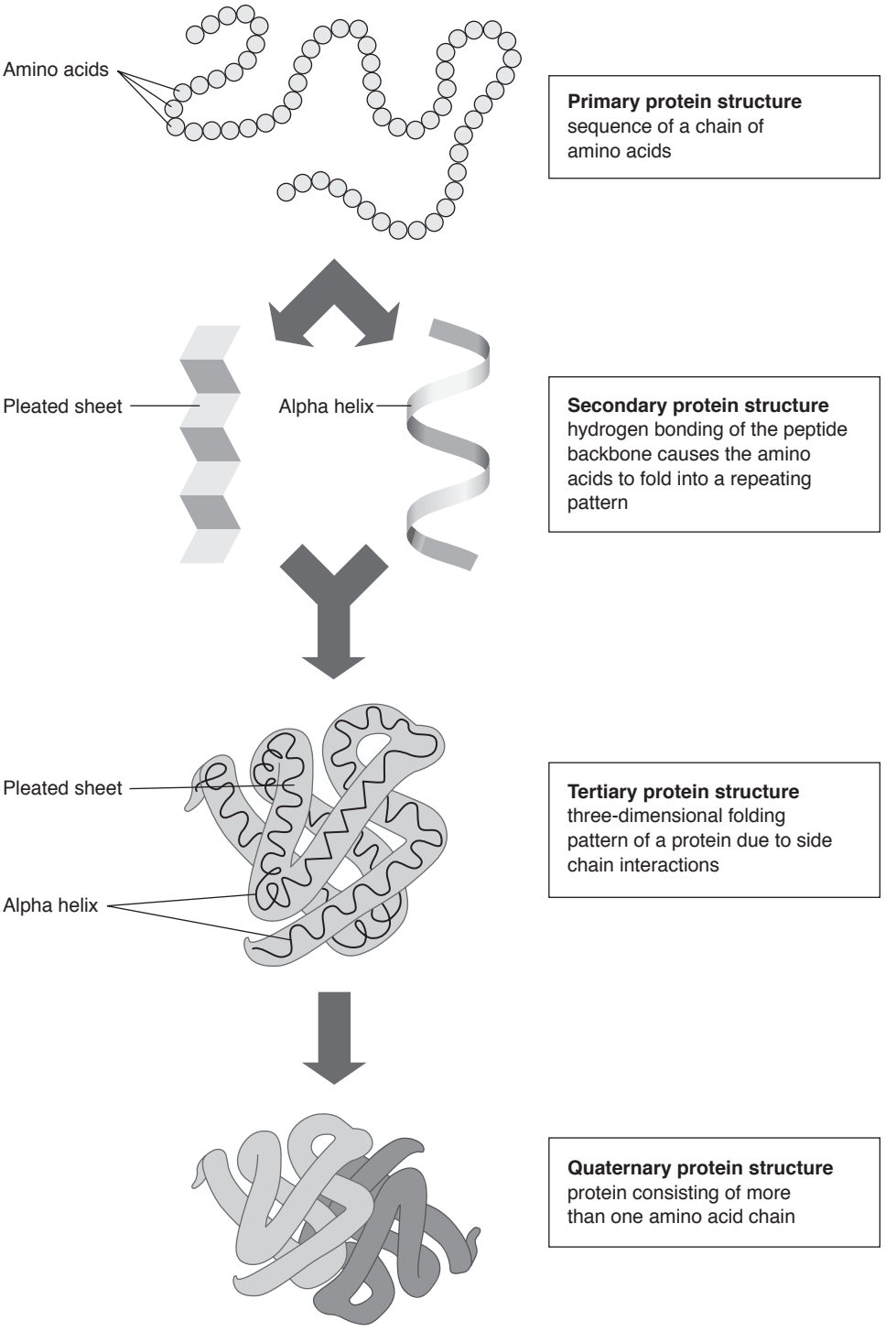

Figure 4.3 Protein structure in primary, secondary, tertiary, and quaternary configurations

Quality of proteins

In a typical day, most people consume about 100 grams of protein. This is almost twice their requirement given that the RDA for protein should be 56 grams for a 70-kg man. Most of this protein comes from animal sources such as meat, milk, cheese, and eggs that represent the most concentrated sources of protein. Nuts, seeds, and plants such as legumes also provide a good source of protein. Legumes are special in that they are associated with bacteria that can take nitrogen from the air and incorporate it into protein. Generally speaking, foods of animal origin tend to have larger amounts of certain essential amino acids than do plant-derived foods, and therefore are considered more efficient in terms of being used to make body proteins.

Complete and incomplete proteins

As you might expect, human tissue composition resembles animal tissue more than it does plant tissue. The similarities enable us to use proteins from any single animal source more efficiently to support human growth and maintenance than we do those from any single plant source. For this reason, animal proteins are generally considered high-quality or **complete proteins**, which contain the nine essential amino acids we need in sufficient amounts. Plant sources of protein, except for soybean, are considered low-quality or **incomplete proteins** because they lack adequate amounts of one or more essential amino acids. Proteins from plants have more diverse amino acid patterns that are quite different from those found in the body. Hence, a single plant protein source, such as corn or wheat alone, cannot easily support body growth and maintenance. Corn protein has low amounts of lysine and tryptophan, whereas wheat protein lacks lysine. The amino acids that are missing or in a low quantity are called **limiting amino acids**.

When only low-quality protein foods are consumed, consumption of essential amino acids may be insufficient. Therefore, when compared to high-quality proteins, a greater amount of low-quality protein is needed to meet the needs of protein synthesis. Moreover, once any of the nine essential amino acids in the plant protein we have eaten is used up, further protein synthesis becomes impossible. Because the depletion of just one of the essential amino acids prevents protein synthesis, the process illustrates the all-or-none principle: either all essential amino acids are available or none can be used. The remaining or unused amino acids would then be used for energy needs, or converted into carbohydrate or fat.

Protein complementation

In general, plant proteins are of lower quality than animal proteins, and plants also offer less protein per unit of weight. For this reason, many vegetarians improve the quality of proteins in their diets by combining plant protein foods that are different but have complementary amino acid patterns. When two or more proteins combine to compensate for deficiencies in essential amino acid content in each protein, the proteins are called **complementary proteins**. Protein complementation allows diets containing a variety of plant protein sources to provide all the essential amino acids. This is particularly important for vegetarians and **vegans** because they have a restricted intake of animal product. For example, **lacto-ovo vegetarians** eat no animal flesh but do eat eggs and dairy products such as milk and cheese, whereas **lacto vegetarians** are those who avoid animal flesh and eggs but do consume dairy products. Vegans consume the most restrictive vegetarian diets.

By eating plant proteins with complementary amino acid patterns, essential amino acid requirements can be met without consuming any animal proteins. The amino acids that are most often limited in plant proteins are lysine, methionine, cysteine, and tryptophan. As a general rule, legumes are deficient in methionine and cysteine but high in lysine. Grains, nuts, and seeds are deficient in lysine but high in methionine and cysteine. Corn is deficient in lysine and tryptophan but is a good source of methionine. Therefore, consuming rice, which is limited in amine acid lysine but high in methionine and cysteine, with beans, which are high in lysine but limited in methionine and cysteine, provides enough of all the essential amino acids needed by the body.

The mixed diets that we normally consume generally provide high-quality protein because of protein complementation. Therefore, healthy adults should have little concern about balancing foods to yield the proteins needed to obtain enough of all nine essential amino acids. Even on the plant-based diets, complementary proteins need not be consumed at the same meal by adults. Meeting amino acid needs over the course of a day is a reasonable goal because there is a ready supply of amino acids from those present in the body cells and in the blood (Craig and Mangels 2009, American Dietetic Association 2009). The following are more food choices that provide significant amounts of complementary proteins:

- Barley bean vegetable soup
- Beans and rice or tortillas
- Black bean and corn salad
- Brown rice and black bean burritos
- Brown rice with lentils and apricots
- Corn and black-eyed pea salad
- Grilled cheese sandwich
- Lasagna
- Macaroni and cheese
- Pasta with lentils and kale
- Peanut butter and oatmeal with some berries added
- Peanut butter sandwich
- Pizza
- Quinoa lentil salad
- Tacos filled with beans or lentils
- Whole-grain cereal with soy milk
- Yogurt with nuts.

Food sources of proteins

In a typical day, most people consume about 100 grams of protein. This is almost twice their requirement given that the RDA for protein should be 56 grams for a 70-kg man based on a formula of 0.8 grams of protein per kg of body weight. Most of this protein comes from animal sources such as meat, milk, cheese, and eggs that represent the most concentrated sources of protein. One egg or an ounce of meat contains about 7 grams of protein, and a cup of milk contains 8 grams. Plants also provide a good source of protein (Figure 4.4). Legumes, such as lentils, soybeans, peanuts, peas, kidney beans, and black beans, provide 6 to 10 grams of protein per half-cup serving. Nuts and seeds are also good sources of protein, providing about 5 to 10 grams per quarter-cup serving. As noted earlier, foods of animal origin tend to contain larger amounts of essential amino acids than do plant-derived foods. However, a diet including plant proteins from a variety of sources will easily meet most people's needs.

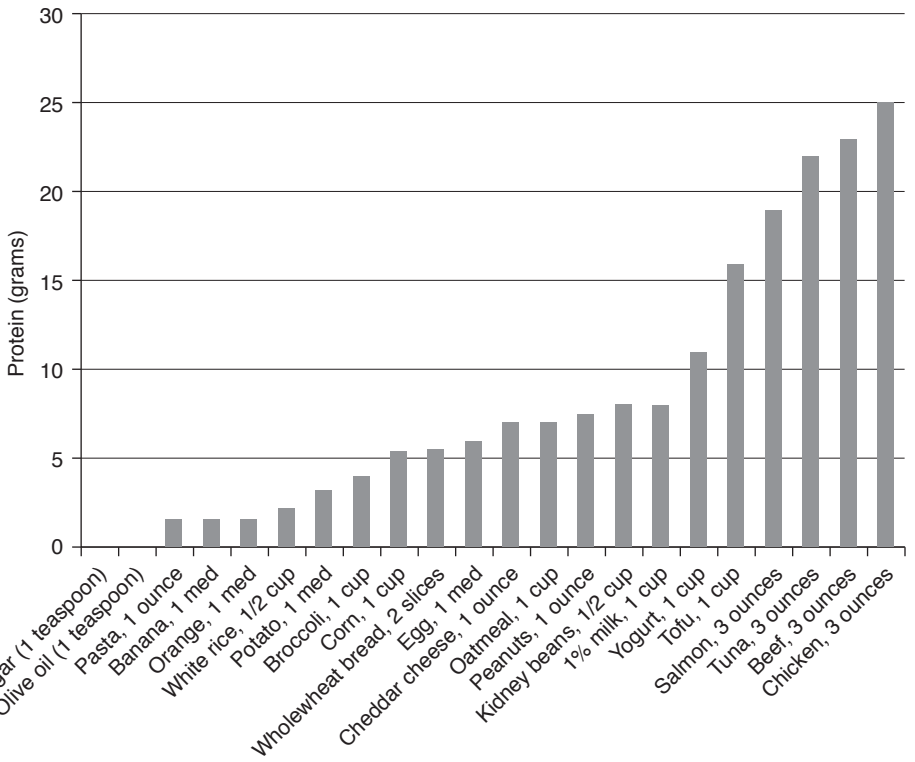

Figure 4.4 Food sources of protein

Major roles of protein in the body

The body uses amino acids to synthesize the hundreds of thousands of proteins it needs. Whenever the body is growing, repairing, or replacing tissues, proteins are involved. Sometimes their role is to become part of structure; other times it is to facilitate or regulate. We rely on foods to supply the amino acids needed to form these proteins. However, only when we also eat enough carbohydrates and fat can food proteins be used most efficiently. If we fail to consume enough calories to meet our needs, some amino acids from proteins are broken down to produce energy instead of being available to replenish and build body proteins.

Structure

Proteins provide most of the structural materials in the body. For example, they are important constituents of muscle, skin, bone, hair, and finger-nails. An example of a structural protein is collagen, which forms a supporting matrix in bones, teeth, ligaments, and tendons. Proteins are also an integral part of the cell membrane, the cytoplasm, and the organelles. The synthesis of structural proteins such as those in skeletal muscle is especially important during periods of active growth and development such as infancy and adolescence. If a person's diet is low in protein for a long period, the processes of protein synthesis will slow down. Over time, skeletal muscles and vital organs such as the heart and liver will decrease in size or volume.

Most vital body proteins are in a constant state of breakdown, rebuilding, and repair. For example, the intestinal tract lining is constantly sloughed off. The digestive tract treats sloughed cells just like food particles, digesting them and absorbing their amino acids. In fact, most of the amino acids released throughout the body may be recycled to become part of the pool of amino acids available for synthesis of future proteins. Overall, protein turnover is a process by which a cell can respond to its changing environment by producing proteins that are needed and degrading proteins that are not needed. It is estimated that an adult makes and degrades about an average of 250 grams of protein each day. Relative to 70 to 100 grams of protein typically consumed, recycled amino acids make an important contribution to total protein metabolism.

Enzymes

Enzymes are protein molecules that speed up the metabolic reactions of the body but are not used up or destroyed in these reactions. All the reactions involved in the production of energy and the synthesis and breakdown of carbohydrates, lipids, proteins, and other molecules are expedited by enzymes. Each reaction requires a specific enzyme with a specific structure. If the structure of the enzyme molecule is altered, it can no longer function in the reaction it is designed to accelerate.

Hormones

Hormones are chemical messengers secreted into the blood by one tissue or organ and act on target cells in other parts of the body. Their primary function is to respond to changes that challenge the body by eliciting the appropriate responses to restore the body's homeostasis or normal conditions. Some hormones are made of lipids; others are made of amino acids and so are classified as peptide or protein hormones. For example, insulin and glucagon are protein hormones.

Movement

Some proteins give cells and organisms the ability to move, contract, and change shape. Actin and myosin are proteins that function in the contraction of muscles. The two proteins slide past each other to shorten the muscle and thus cause contraction. A similar process causes contraction in the heart muscle and in the muscles that cause constriction in the digestive tract, blood-vessels, and body glands. Nearly half of the body's protein is present in skeletal muscle, and adequate protein intake is required to form and maintain muscle mass throughout life.

Transport

Proteins transport substances throughout the body and into and out of the individual cells. Transport proteins in the blood carry substances from one organ to another. For example, hemoglobin, the protein in the red blood cells, binds oxygen in the lungs and transports it to other organs of the body. The proteins in lipoproteins are needed to transport lipids from the intestines and liver to body cells. Some vitamins, such as vitamin A, must be bound to a specific protein to be transported in the blood. When protein is deficient, the nutrients that require protein for transport cannot travel to the cells. For this reason a protein deficiency can cause a vitamin A deficiency, even if

consumption of vitamin A from diet is adequate. At the cellular level, transport proteins present in cell membranes help move substances such as glucose and amino acids across the cell membrane. For example, transport proteins in the intestinal mucosa are necessary to absorb glucose and amino acids from intestinal lumen into the mucosal cells.

Regulation of fluid balance

Most of the body is made of water. This important fluid is found both inside of cells (intracellular space) and outside of cells (extracellular space). In addition, the extracellular space can be further divided into that found in blood and lymph vessels (intravascular fluid) and between cells (interstitial fluid). The amount of fluid in these spaces is highly regulated by a variety of means, some of which involve proteins. For example, a protein called albumin is present in the blood in relatively high concentrations. As the blood circulates through the capillaries, fluid and nutrients in the blood get pushed out into the interstitial space in part because of blood pressure and the narrowness of the capillaries. However, albumin remains in the blood-vessels, gradually increasing in concentration as more fluid is lost. When the albumin concentration reaches a certain level in the blood, albumin draws some of the interstitial fluid back into the blood-vessels via **osmosis**, partially counteracting the force of blood pressure. Osmosis is the movement of water molecules across a partially permeable membrane from an area of high water potential (low solute concentration) to an area of low water potential (high solute concentration).

With an inadequate consumption of protein, the concentration of proteins in the blood drops below normal. Excessive fluid then builds up in the surrounding tissues because the counteracting force produced by blood proteins is too weak to pull enough of the fluid back from the tissues into the blood-vessels. As fluids accumulate in the tissues, the tissues swell, causing **edema**. Edema is associated with a variety of medical problems, so its cause must be identified. An important step in diagnosing the cause is to measure the concentration of blood proteins such as albumin.

Regulation of acid–base balance

The chemical reactions of metabolism require a specific level of acidity, or pH, to function properly. In the gastrointestinal tract, acidity levels vary widely. The digestive enzyme pepsin works best in the acid environment of the stomach, whereas the pancreatic enzymes operate most effectively in the more neutral environment of the small intestine. Inside the body, large fluctuations in pH can prevent metabolic reactions from proceeding. Proteins both within cells and in the blood help prevent major changes in acidity. For example, the protein hemoglobin in red blood cells helps neutralize acid produced from cellular respiration, so that the pH of blood can always be maintained relatively neutrally. Recall that components of amino acids including the side chains carry charges. In other words, they can accept and donate charged hydrogen ions easily. When hydrogen ion concentration in the blood is too high, proteins can bind excess hydrogen ions. Conversely, proteins can release hydrogen ions into the blood when the hydrogen concentration is too low.

Protection as antibodies

Protein can also defend the body against disease. A virus, whether it is one that causes flu, smallpox, measles, or the common cold, enters the cells and multiplies there. One

virus may produce over 100 replicas of itself within an hour or so. Each replica can then burst out and invade different cells. Such a process of virus multiplication will ultimately cause diseases. Fortunately, when the body detects these invading agents, it manufactures antibodies, giant protein molecules designed specifically to combat them. Each antibody has a unique structure that allows it to attach to a specific invader. When an antibody binds to an invading substance, the production of more antibodies is stimulated, and other parts of the immune system are activated to help destroy the invaders. In a normal, healthy individual, most diseases never have a chance to get started because of antibodies. Without sufficient protein, however, the body cannot maintain an adequate level of antibodies to resist diseases.

As a source of energy during times of need

Some amino acids may also be used for glucose synthesis and energy production as well as energy storage as fats. Together, these processes allow the body to (1) maintain an appropriate level of blood glucose, and (2) store excess energy for later use when dietary energy intake is more than adequate. When the body's available supply of energy is low, it first turns to glycogen and fatty acids. However, when glycogen is depleted and fatty acid reserves reduce, the body then dismantles its tissue proteins and converts some amino acids into glucose via gluconeogenesis. In addition, many cells can harvest the energy stored in amino acids by oxidizing them directly. Thus, over time, energy deprivation always causes wasting of lean body tissue in addition to fat loss. An adequate supply of carbohydrates and fats spares amino acids from being used for energy and allows them to perform their unique roles.

During the times of glucose and energy excess, the body redirects the flow of amine acids away from gluconeogenesis and ATP-producing pathways. To do this, the nitrogen-containing group of each amino acid is removed and converted into ammonia in the liver via a process called **deamination**. The remaining carbon skeleton is then converted into lipids and stored in adipose tissue. Thus, eating extra protein during times of glucose and energy sufficiency contributes to fat stores, not to muscle growth.

Summary

- Proteins differ chemically from carbohydrates and lipids because they contain nitrogen in addition to sulfur, phosphorus, and iron. Body proteins are made from individual amino acids that are bonded together. The sequential order of amino acids determines the protein's ultimate shape and function.
- Of the 20 amino acids used by the body, 9 must be consumed from foods (essential) and the rest can be synthesized in the body (nonessential).
- High-quality (complete) protein foods contain ample amounts of all nine essential amino acids. They are mainly obtained from animal sources. Low-quality (incomplete) protein foods lack sufficient amounts of one or more essential amino acids. This is typical of plant foods, but different types of plant foods eaten together often complement each other's amino acid deficits.
- Proteins form important body components, such as muscle, connective tissue, transport proteins in the blood, enzymes, and some hormones. The carbon chains of proteins may be used to produce glucose or fat if necessary.

Case study: choosing a healthy vegetarian diet

Catlin is 26 years old and weighs 143 lbs. She decided to stop eating meat a year ago. Now that she is studying protein in her nutrition class, she has become concerned that her vegetarian diet isn't meeting her needs. She recorded her food intake for one day and then used an online database to calculate her protein intake. Her analysis is shown in Table 4.2.

Table 4.2 Analysis of Catlin's food intake

Food	*Serving*	*Protein (g)*
Breakfast		
Nuts	1/4 cup	3.6
Low-fat milk	1/2 cup	4
Orange juice	3/4 cup	0.8
Toast, wheat	2 pieces	5
Peanut butter	1 tablespoon	4
Coffee	1 cup	0
Lunch		
Lentil soup	1/2 cup	4
Rice	1 cup	6
Banana	1 medium	1
Apple juice	1 cup	0
Dinner		
Green salad w/dressing	1 cup	1
Rice	1 tablespoon	6
Curried potatoes and chickpeas	1/2 cup	5.5
Yogurt plain	1/2 cup	6
Poori (fried bread)	1 piece	2.5
Ice cream	1/2 cup	2
Total		51.4

Questions

- Does Catlin get enough protein? Compare her intake with the RDA for someone her age and size.
- Define the term "complementary proteins."
- Does her diet contain complementary proteins? List protein sources in her diet and explain how they complement each other.
- If Catlin decides to become a vegan, what could she substitute for her dairy foods in order to meet her protein needs?

Review questions

1 Describe the structure of amino acids. How does the chemical structure of proteins differ from the structure of carbohydrates and lipids?
2 What are essential amino acids? Why is it important for essential amino acids lost from the body to be replaced in the diet?

3 Define terms "peptide bone," "deamination," "transamination," and "nitrogen balance."
4 Describe the concept of complementary proteins. How can vegetarians meet their protein needs without eating meat?
5 Briefly describe the organization of proteins. How can this organization be altered or damaged? What might be a consequence of damaged protein organization?
6 Describe the roles played by protein in the body.

Suggested reading

1 Burke LM, Collier GR, Hargreaves M (1998) Glycemic index – a new tool in sport nutrition? *International Journal of Sport Nutrition*, 8: 401–415.
The glycemic index provides a way to rank foods rich in carbohydrate according to the glucose response following their intake. This review article discusses specifically how the concept of the glycemic index may be applied to training and sports competitions.
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Glossary

Complementary proteins proteins that can be combined to compensate for deficiencies in essential amino acid content in each protein.
Complete proteins proteins that contain all the nine essential amino acids.
Deamination a process in which the nitrogen-containing group of an amino acid is removed and converted into ammonia in the liver.
Denaturation a process in which proteins or nucleic acids unfold to lose their tertiary and secondary structure.
Edema swelling of tissue caused by fluid accumulation in the interstitial space.
Essential or indispensable amino acids amino acids that cannot be made by the body and must be consumed in the diet.
Incomplete proteins proteins that lack adequate amounts of one or more essential amino acids.
Lacto-ovo vegetarians those who eat no animal flesh but do eat eggs and dairy products such as milk and cheese.
Lacto vegetarians those who avoid animal flesh and eggs but do consume dairy products.
Limiting amino acids the amino acids that are missing or in a low quantity.
Nonessential or dispensable amino acids amino acids that can be made by the human body and are not required in the diet.
Osmosis the movement of water molecules across a partially permeable membrane from an area of high water potential (low solute concentration) to an area of low water potential (high solute concentration).

Peptide bond the chemical bond formed between the acid group of one amino acid and the nitrogen atom of the next amino acid.

Transamination a process in which the amino group from one amino acid is transported to a carbon-containing molecule to form a different amino acid.

Vegans those who consume the most restrictive vegetarian diets.

5 Micronutrients
Vitamins

Contents

Key terms

- Bioavailability
- Enrichment
- Free radical
- Microcytic hypochromic anemia
- Osteomalacia
- Pernicious anemia
- Reactive oxygen species
- Rickets
- Vitamin toxicity
- Collagen
- Fortification
- Macrocytic anemia
- Osteoclasts
- Osteoporosis
- Provitamins
- Retinoids
- Vitamins

Overview

The effective regulation of all metabolic processes requires a delicate blending of food nutrients in the watery medium of the cell. Of special significance in this regard are micronutrients, the small quantities of vitamins and minerals that facilitate energy transfer and tissue synthesis. The term "vitamin" was coined in 1912 by Polish biochemist Casimir Funk, who originally used the word "*vitamine*" to refer to substances which are amines that contain an amino group and are vital to life. Today, we know that vitamins are vital to life, but they are not all amines, so the "e" has been dropped, and the term "vitamin" refers to all these substances. Initially, the vitamins were named alphabetically in approximately the order in which they were identified: A, B, C, D, and E. The B vitamins were first thought to be one chemical form but were later found to be many different subgroups, so the alphabetical name was broken down by numbers that reflect the chronological order. For example, thiamin was the first B vitamin identified in 1937, and vitamin B12 was the last structure that was characterized in 1948. Currently, vitamins B6 and B12 are the only ones that are still commonly referred to by their numbers. Thiamin, riboflavin, and niacin were originally referred to as vitamins B1, B2, and B3, respectively, but they now often stand on their own names.

What are vitamins?

Vitamins are organic compounds that are essential in the diet in small amounts to promote and regulate body functions necessary for growth, reproduction, and maintenance of the body. Vitamins are generally essential in human diets because they cannot be synthesized in the body or because their synthesis can be decreased by environmental factors. Notable exceptions to having a strict dietary need for a vitamin are vitamin A, which we can synthesize from certain pigments in plants, vitamin D, synthesized in the body if the skin is exposed to adequate sunlight, niacin, synthesized from the amino acid tryptophan, and vitamin K and biotin, synthesized to some extent by bacteria in the intestinal tract.

To be qualified as a vitamin, a compound must meet the following two criteria to be an essential nutrient: (1) the body is unable to synthesize enough of the compound to maintain health; and (2) absence of the compound from the diet for a certain period produces deficiency symptoms that, if caught in time, are quickly cured when the substance is resupplied. A substance does not qualify as a vitamin merely because the body cannot make it. Evidence must suggest that health declines when a substance is not consumed.

Vitamins differ from carbohydrates, lipids, and proteins in the following ways:

- Structure: vitamins are individual units; they are not linked together as are the molecules glucose, fatty acids, and amino acids.

- Function: vitamins do not provide energy when broken down. They assist enzymes that catalyze energy-yielding pathways involving carbohydrates, lipids, and proteins.
- Food contents: the amounts of vitamins we ingest daily from foods and amounts we require are measured in micrograms (μg) or milligrams (mg), rather than grams (g).

Classification of vitamins

Vitamins have traditionally been grouped based on their solubility in water or fat. This chemical characteristic allows generalizations to be made about how they are absorbed, transported, excreted, and stored in the body. The water-soluble vitamins include the B vitamins and vitamin C. The fat-soluble vitamins include vitamins A, D, E, and K.

Vitamins in the diet

Almost all foods contain some vitamins. Generally speaking, grains are good sources of thiamin, niacin, riboflavin, pantothenic acid, and biotin. Meat and fish are good sources of all the B vitamins. Milk provides riboflavin and vitamins A and D; leafy greens provide folate, vitamins A, E, and K; citrus fruit provides vitamin C; and vegetable oils are high in vitamin E. The vitamin content, however, can be affected by cooking, storage, and processing. The vitamins naturally found in foods can be washed away during preparation or destroyed by cooking. Exposure to light and oxygen can also cause vitamin loss. Food processing can both cause nutrient losses and add nutrients to food. The addition of nutrients to foods is called **fortification**. The added nutrients may or may not have been present in the original food. **Enrichment** is a type of fortification in which nutrients are added for the purpose of restoring those lost in processing to the same or a higher level than originally present. For example, the milling of wholegrain wheat to make white flour results in the loss of the nutrients contained in the bran and germ. Enrichment adds back the vitamins thiamin, niacin, and riboflavin, and the mineral iron. Foods that are staples of a diet are often fortified to prevent vitamin or mineral deficiencies and to promote health in the population. For example, milk is fortified with vitamin D to promote bone health, and grains are fortified with folic acid to reduce the incidence of birth defects. Some foods are fortified because they are used in place of other foods that are good sources of an essential nutrient. For example, margarine is fortified with vitamin A because it is often used instead of butter, which naturally contains vitamin A.

Vitamin toxicity

Vitamin toxicity is a condition in which a person develops symptoms as side effects from taking massive doses of vitamins. For most water-soluble vitamins, when they are consumed excessively, the kidneys can efficiently filter the excess from the blood, and excrete them via urine. However, some water-soluble vitamins, such as niacin, Vitamins B6 and B12, and vitamin C can cause toxic effects when consumed in large amounts. For example, when taken in large doses, vitamin C can be at risk for developing kidney and gall-bladder stones, niacin can cause flushing of the skin, nausea, diarrhea, and liver damage, and vitamins B6 and B12 can produce nerve problems. In contrast to the water-soluble vitamins, fat-soluble vitamins are not readily excreted, so some can easily accumulate in the body and cause toxic effects. Among those fat-soluble vitamins, toxicity of vitamin A is the most frequently observed. The toxic effects associated with each of the fat-soluble vitamins are discussed in later sections of this chapter.

Preserving vitamins in foods

Substantial amounts of vitamins can be lost from the time a fruit or vegetable is picked until it is eaten. The water-soluble vitamins, particularly thiamin, vitamin C, and folate, can be destroyed with improper storage and excessive cooking. Heat, light, exposure to the air, cooking in water, and alkalinity are all factors that can destroy vitamins. The sooner a food is eaten after harvest, the less chance of nutrient loss.

In general, if the food is not eaten within a few days, freezing is the best preservation method to retain nutrients. Fruits and vegetables are often frozen immediately after harvesting, so frozen vegetables and fruits are often as nutrient-rich as freshly picked ones. As part of the freezing process, vegetables are quickly blanched in boiling water. This destroys the enzymes that would otherwise degrade the vitamins. Table 5.1 provides some tips to aid in preventing vitamin loss.

Vitamins in the digestive tract

About 40 to 90 percent of the vitamins in foods are absorbed, primarily in the small intestine. The composition of the diet and conditions in the body, however, may influence **bioavailability**, a general term that refers to how well a nutrient can be absorbed and used by the body. The bioavailability of a specific nutrient may also be affected by other foods and nutrients in the diet. For example, the amount of fat in the diet affects the bioavailability of fat-soluble vitamins because they are absorbed along with dietary fat. In other words, fat-soluble vitamins are poorly absorbed when the diet is very low in fat. The transport mechanism by which vitamins are absorbed also determines the amount that enters the body. The fat-soluble vitamins are easily absorbed by simple diffusion. Many of the water-soluble vitamins, however, depend on energy-requiring transport systems or binding molecules in the gastrointestinal tract in order to be absorbed. For example, thiamin and vitamin C are absorbed by energy-requiring transport systems, riboflavin and niacin require carrier proteins for absorption, and vitamin B12 must be bound to a protein produced in the stomach before it can be absorbed in the intestine. The quantity of vitamins in foods can be easily determined using an analytic approach. However, determining the bioavailability of a vitamin is a more complex task because it depends on many factors, including (1) efficiency of digestion and time of transit through the GI tract; (2) previous nutrient intake and nutritional status; (3) other foods consumed at the same time; (4) methods of preparation (e.g., raw, cooked, or processed); and (5) source of the nutrients (e.g., synthetic, fortified, or naturally occurring).

Some of the vitamins are available from foods in inactive forms known as vitamin precursors, or **provitamins**. Once inside the body, the precursor is converted into an active form of the vitamin. Thus, in measuring a person's vitamin intake, it is important to count both the amount of the active vitamin and the potential amount available from its precursors.

Vitamins in the body

Once absorbed into the blood, vitamins must be transported to the cells. Despite their solubility in water, most of the water-soluble vitamins are bound to blood proteins for transport. Fat-soluble vitamins must be incorporated into lipoproteins or bound to transport proteins in order to be transported in the aqueous environment of the blood. For example, vitamins A, D, E, and K are all incorporated into chylomicrons for transport from the intestine. The amount of vitamins delivered to the tissues depends on the availability of the transport protein.

Table 5.1 Tips for preventing nutrient loss

What to do	*Why*
Keep fruits and vegetables cool	Chilling will reduce the degradation of vitamins by enzymes
Refrigerate fruits and vegetables that have been put in moisture-proof, airtight containers	This will help keep all nutrients and minimize oxidation of vitamins
Trim, peel, and cut fruits and vegetables minimally	Oxygen breaks down vitamins faster when more surface is exposed, and outer leaves of most vegetables have higher values of vitamins and minerals than inner tender leaves and/or stems
Rinse fruits and vegetables before cutting	This will prevent nutrients from being washed away
Use microwave oven or steam vegetables in a small amount of water	More nutrients are retained when there is less contact with water
Add vegetables after water has come to the boil	More nutrients are retained with shorter cooking time
Minimize reheating food	Prolonged reheating reduces vitamin content
Do not add baking soda to vegetables to enhance the green color	Alkalinity destroys most vitamins, especially vitamin D and thiamin
Do not add fats to vegetables during cooking if you plan to discard the liquid	Fat-soluble vitamins will be lost in discarded fat

The body has the ability to store and excrete vitamins. This helps regulate and maintain an adequate amount of vitamins present in the body. Except for vitamin K, the fat-soluble vitamins are not readily excreted from the body. In contrast, with the exception of vitamin B12, excess amounts of the water-soluble vitamins are generally lost from the body rapidly, partly because the water in cells dissolves these vitamins and excretes them out of the body via the kidneys. Because of the limited storage of many vitamins, they should be consumed in the diet regularly, although an occasional lapse in the intake of even water-soluble vitamins generally causes no harm. Symptoms of a vitamin deficiency occur only when a vitamin is lacking in the diet for an extended period and body stores are essentially exhausted. For example, an average person must consume no vitamin C for about 30 days before developing the first symptoms of deficiency of this vitamin.

Fat-soluble vitamins

Fat-soluble vitamins are typically absorbed in the small intestine. This requires the presence of other lipids as well as the action of bile. Fat-soluble vitamins are circulated away from the small intestine in the lymph via chylomicrons, which are large lipoprotein particles that consist primarily of triglycerides, and eventually enter the blood. In the blood, fat-soluble vitamins are circulated as components of very low-density lipoproteins (VLDL) or bound to transport proteins. Because most of the fat-soluble vitamins are stored in the body, people can eat less than their daily need for days, weeks, or even months or years without ill-effects. In fact, consuming large amounts of them, especially in supplement form, can result in toxicities, sometimes with serious consequences. Most fat-soluble vitamins are involved in processes such as regulation of gene expression, cell maturation, and stabilization of free radicals. Table 5.2 gives an overview of the functions and sources as well as deficiency diseases, and toxicity symptoms associated with each of the four fat-soluble vitamins.

Vitamin A

Vitamin A is found pre-formed and in precursor or provitamin forms in our diet. Preformed vitamin A compounds are known as **retinoids**, which include retinol, retinoic acid, and retinal. They are found in animal foods such as liver, fish, egg yolks, and dairy products (Table 5.3). Margarine and non-fat or reduced-fat milk are fortified with vitamin A because they are often consumed in place of butter and whole milk, which are good sources of this vitamin. Plant sources of vitamin A include carrots, cantaloupe, apricots, mangoes, and sweet potatoes that contain yellow-orange pigments called carotenoids. Beta-carotene, the most potent precursor, is found in carrots, squash, and other red and yellow vegetables and fruits as well as in leafy greens where the yellow pigment is masked by green chlorophyll. Other carotenoids that provide some provitamin A activity include alpha-carotene found in leafy green vegetables, carrots, and squash, and beta-cryptoxanthin found in corn, green peppers, and lemons. Lutein, lycopene, and zeaxanthin are carotenoids with no vitamin A activity. To help consumers identify food sources of vitamin A, labels on packaged foods must include the vitamin A content as a percentage of the daily value. All forms of vitamin A in the diet are fairly stable when heated but may be destroyed by exposure to light and oxygen.

Vitamin A has many roles, including aiding vision, growth, and reproduction. In addition, it is needed for maintaining a healthy immune system and building strong bones. Vitamin A is involved in the perception of light. In the eye, the retinal form of the vitamin combines with the protein opsin to form the visual pigment rhodopsin.

Table 5.2 Functions, sources, deficiency diseases, and toxicity symptoms for fat-soluble vitamins

Vitamin	*Major function*	*Deficiency*	*Toxicity*	*Food sources*
Vitamin A	• Growth • Reproduction • Vision • Cell differentiation • Immune function • Bone health	• Night blindness • Xerophthalmia • Hyperkeratosis	• Hypercarotenemia • Blurred vision • Birth defects • Liver damage • Osteoporosis	• Liver • Pumpkin • Sweet potato • Carrot
Vitamin D	• Calcium homeostasis • Bone health • Cell differentiation	• Rickets • Osteomalacia • Osteoporosis	• Hypercalcemia	• Fish • Mushrooms • Fortified milk • Fortified cereals
Vitamin E	• Antioxidant • Cell membranes • Eye health • Heart health	• Neuromuscular problems • Hemolytic anemia	• Hemorrhage	• Tomatoes • Nuts and seeds • Spinach • Fortified cereals
Vitamin K	• Coenzyme • Blood clotting • Bone health • Tooth health	• Bleeding	• No known effects	• Kale • Spinach • Broccoli • Brussels sprouts

Table 5.3 Food sources of vitamin A

Food item	*Amount*	*Vitamin A content (μg)*
Fried beef liver	1 ounce	3025
Sweet potato	1/2 cup	958
Cooked carrots	1/2 cup	885
Spinach	2/3 cup	494
Mango	1 med	402
Squash	2/3 cup	244
Eggs	2 large	185
2% milk	1 cup	175
Broccoli	1 cup	138
Apricots	3 med	137
Cheddar cheese	1 ounce	78
Margarine	1 teaspoon	52
Salmon	3 ounces	45
Butter	1 teaspoon	45
Raw tomato	1/2 cup	40
Orange	1 med	25
Chicken	3 ounces	10

Note
RDA: 900 μg/day for men and 700 μg/day for women.

Rhodopsin helps transform the energy from light into a nerve impulse that is sent to the brain. This nerve impulse allows us to see. The visual cycle begins when light passes into the eye and strikes rhodopsin. Each time this cycle occurs, some retinal is lost and must be replaced by retinol from the blood. The retinol is then converted into retinal in the eye. When vitamin A is deficient, there is a delay in the regeneration of rhodopsin, which causes difficulty in adapting to dim light after experiencing a bright light, a condition called night blindness. Night blindness is one of the first and more easily reversible symptoms of vitamin A deficiency.

Vitamin A affects cell differentiation through its effect on gene expression. In order to affect gene expression, the retinoic acid form of vitamin A enters specific target cells. Inside the nucleus of these target cells, retinoic acid binds to protein receptors to form a retinoic acid–protein receptor complex. This complex then binds to regulatory regions of DNA, which then changes the amount of messenger RNA that is made by the gene. This increases protein synthesis, thereby affecting various cellular functions. For example, vitamin A turns on a gene that makes an enzyme in liver cells, which enables the liver to make glucose by gluconeogenesis.

The ability of vitamin A to regulate the growth and differentiation of cells makes it essential throughout life for normal reproduction, growth, and immune function. In reproduction, vitamin A is believed to play a role during early embryonic development by directing cells to form the shapes and patterns needed for a completely formed organism. Poor overall growth is an early sign of vitamin A deficiency in children. Vitamin A affects the activity of cells that form and break down bone, and a deficiency early in life can cause abnormal jawbone growth, resulting in crooked teeth and poor dental health. Via its role in regulating cell differentiation, Vitamin A is also important for producing the different types of immune cells and for stimulating the activity of specific immune cells.

The recommended daily amount (RDA) for vitamin A is set at 900 μg per day for men and 700 μg per day for women. These RDA values are based on the amount needed to

maintain normal body stores. There is no recommendation to increase intake above this level for older adults. The RDA is increased in pregnancy to account for the vitamin A that is transferred to the fetus and during lactation to account for the vitamin A lost in milk. Consumption of vitamin A should not exceed 3000 µg per day. Above this upper limit, other possible side effects include an increased risk of hip fracture and poor pregnancy outcomes. The consumption of large amounts of vitamin A-yielding carotenoids does not cause toxic effects. This is because (1) they are less well absorbed, and (2) their rate of conversion into vitamin A is relatively slow and regulated.

Vitamin D

Vitamin D has an interesting and unique place among the nutrients. Although this vitamin is found in food, the major source of vitamin D is exposure to sunlight. For most individuals, exposure to ultraviolet rays from sunlight provides at least 80 percent of their vitamin D needs. For this reason, vitamin D is also known as sunshine vitamin, and many nutritional scientists consider it to be a conditionally essential nutrient. Egg yolks, butter, whole milk, fatty fish, fish oil, and mushrooms are some of the few foods that naturally contain vitamin D (Table 5.4). However, most liquid and dried milk products as well as breakfast cereals are fortified with vitamin D, and most dietary vitamin D comes from these foods. Vitamin D is relatively stable and is not destroyed during food preparation, processing, and storage.

Two major forms of vitamin D that are important to humans are vitamin D_2, or ergocalciferol, and vitamin D_3, or cholecalciferol. Vitamin D_2 is made naturally by plants, and vitamin D_3 is made naturally by the body when the skin is exposed to ultraviolet radiation in sunlight. Both forms are converted into 25-hydroxyvitamin D in the liver. 25-hydroxyvitamin D then travels through the blood to the kidneys, where it is further modified to 1,25-dihydroxyvitamin D, or calcitriol, the active form of vitamin D in the body. The most accurate method of evaluating a person's vitamin D status is to measure the level of 25-hydroxyvitamin D in the blood.

Table 5.4 Food sources of vitamin D

Food item	*Amount*	*Vitamin D content (µg)*
Baked herring	1 ounce	44.4
Smoked eel	1 ounce	25.5
Salmon	3 ounces	6.0
Sardine	1 ounce	3.4
2% milk	1 cup	2.5
1% milk	1 cup	2.5
Eggs	2 large	1.3
Total cereal	3/4 cup	1.0
Soy milk	1 cup	1.0
Margarine	1 teaspoon	0.65
Chicken	3 ounces	0.4
Beef liver	2 ounces	0.4
Cheddar cheese	1.5 ounces	0.25
Butter	1 teaspoon	0.15

Notes
The adequate intake (AI) is 5 µg per day for people under age 50 and increase two to three times for older adults. An RDA could not be set for vitamin D because the amount produced by sunlight exposure is too variable between individuals.

Vitamin D plays an important role in regulating calcium concentrations in the blood. This requires several organs, including the small intestine, kidneys, and bone. Vitamin D, or more precisely 1,25-dihydroxyvitamin D, or calcitrol, increases calcium absorption in the intestine, decreases calcium excretion in urine, and facilitates the release of calcium from bone. In this context, vitamin D acts like a hormone because it is produced in one organ, the skin, and affects other organs such as intestine, kidneys, and bone. In small intestine, vitamin D up-regulates several genes that code for proteins required for the transport of dietary calcium into the cells. In other words, vitamin D is involved in cell signaling. Without vitamin D, these proteins are not made, and calcium absorption is severely limited. In the kidneys, vitamin D, along with parathyroid hormone, causes the kidneys to reduce their excretion of calcium into urine. As a result, more calcium remains in the blood. Vitamin D also acts with parathyroid hormone to stimulate bone breakdown by **osteoclasts** and therefore the release of calcium into the blood. While calcium in bones is important for their structure, calcium in the blood has additional physiological functions. For example, it is needed for muscle contraction, blood pressure regulation, and the conduction of neural impulses. Without vitamin D to help maintain adequate levels of calcium in the blood, these vital functions would be impaired. Because of the close relationship between vitamin D and calcium in the body, the US Food and Drug Administration (FDA) encourages vitamin D fortification of milk. It must be noted that regardless of whether consumed in the diet or produced in the skin, vitamin D must be activated before the body can use it. Such an activation process occurs in the liver and kidneys. The role played by vitamin D in regulating calcium homeostasis is illustrated in Figure 5.1.

Vitamin D is also involved in a wide variety of other functions such as regulation of gene expression and cell differentiation. As with vitamin A, vitamin D moves into the nucleus of the cell for the subsequent stimulation of the genes coding for specific proteins. For example, vitamin D causes immature bone cells to become mature bone

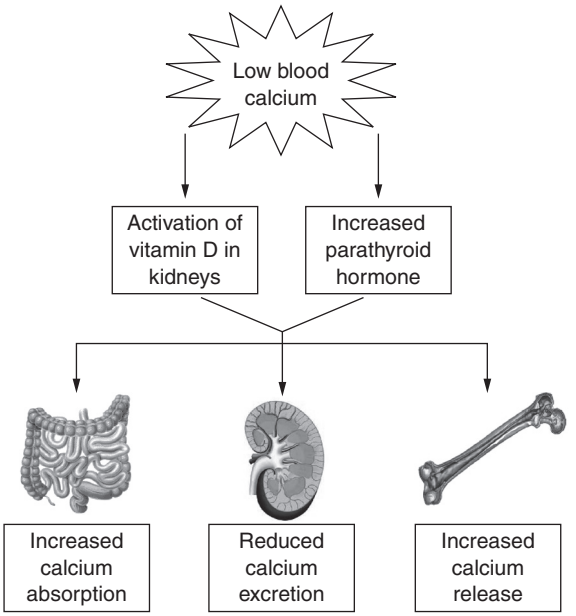

Figure 5.1 Vitamin D and its role in the regulation of calcium homeostasis

marrow cells and allows certain intestinal epithelial cells to differentiate into mature enterocytes. As such, vitamin D plays a role in maintaining bone health and gastrointestinal function. Studies also reveal that vitamin D may help prevent certain types of cancers such as those of the colon, breast, skin, and prostate (Bikle 2004, Gross 2005, Harris and Go 2004, Holick 2004, Walsh 2004). Early epidemiologic research showed that incidence and death rates for certain cancers were lower among individuals living in southern latitudes, where levels of sunlight exposure are relatively high, than among those living in northern latitudes. It is believed that such a protective role of vitamin D is accomplished through the local production of 1,25-dihydroxyvitamin D in affected tissues other than the kidneys. Researchers have hypothesized that 1,25-dihydroxyvitamin D can decrease the risk of the cells being transformed into a malignant state by controlling cell growth and cellular differentiation (Holick and Chen 2008). When vitamin D is deficient, dietary calcium cannot be absorbed efficiently. As a result, calcium is not available for proper bone mineralization and abnormalities in bone structure occur. Vitamin D deficiency in infants and children who are in active stages of growth may result in inadequate bone mineralization – a disease called **rickets**. Although fortifying food with vitamin D has essentially eliminated rickets in the United States, a significant number of cases have still been reported, especially in inner-city children who have a poor diet and whose exposure to sunlight is limited. Rickets is also a significant public health concern in other parts of the world (Calvo *et al.* 2005). Children with rickets have slow growth and characteristically bowed legs or knocked knees caused by the bending of weak, long bones that cannot support the stress of weight-bearing activities, such as walking.

In adults, the vitamin D deficiency disease comparable to rickets is called **osteomalacia**. Because bone growth is complete in adults, osteomalacia does not cause deformities, but bones are weakened because not enough calcium is available to form the mineral deposits needed to maintain healthy bone. Symptoms of osteomalacia include diffuse bone pain and muscle weakness. People with osteomalacia are at increased risk of bone fracture. Osteomalacia is common in adults with kidney failure because the conversion of vitamin D from inactive to active forms is reduced. The elderly are at risk for vitamin D deficiency because the ability to produce vitamin D in the skin decreases with age mainly because older adults typically cover more of their skin with clothing and spend less time in the sun than their younger counterparts. In addition, the elderly tend to have a lower intake of dairy products. Vitamin D deficiency can also result in demineralization of bone, ultimately leading to a disease called **osteoporosis**, a condition characterized by a decrease in bone density and strength, resulting in fragile bones that can be frequently fractured. Osteoporosis is a serious chronic disease, and researchers estimate that more than 28 million Americans (1 in 10 people) suffer from it. To help prevent both osteomalacia and osteoporosis, people over 50 years of age are advised to get at least 15 minutes of sun exposure each day when possible and to increase their vitamin D intake. In some cases, vitamin D supplements may be necessary. With more emerging roles of vitamin D being discovered, it is now believed that vitamin D deficiency can also increase risk for developing cardiovascular disease, diabetes, muscle weakness and pain, cognitive impairment in older adults, and certain types of cancer.

An RDA could not be set for vitamin D because the amount produced by sunlight exposure is too variable between individuals. Consequently, a notation of "adequate intake" or AI was used to provide a guideline for vitamin D intake. AI for adult males and females is set at 5μg per day, which may be achieved by drinking two cups of vitamin D-fortified milk. This AI value was given based on the assumption that no vitamin D is synthesized in the skin. If there is sufficient sun exposure, dietary vitamin D is not needed. This assumption is made because of the variation in the extent to which

synthesis from sunlight meets the requirement. The amount synthesized in the skin is affected by skin pigmentation, climate, season, clothing, pollution, tall buildings that block sunlight, and the use of sunscreens. The AI of vitamin D for infants and children is the same as for adults. This is to allow sufficient vitamin D for bone development during periods of rapid growth. Infants and children who are exposed to sunlight for about half an hour per day do not require supplemental vitamin D. The AI for adults 50 to 70 years of age is 10 µg per day to prevent bone loss during periods of low sun exposure. In adults aged 70 or older, the AI is 15 µg per day to maintain blood values of vitamin D and to prevent skeletal fracture. The consumption of vitamin D should not exceed 50 µg per day. Too much vitamin D can result in the over-absorption of calcium which eventually leads to calcium deposits in the kidneys and other organs, and causes metabolic disturbances and cell death. The most accurate way to measure how much vitamin D is in your body is the 25-hydroxyvitamin D blood test. A level of 20 to 50 ng/mL is considered adequate for healthy people. A level less than 12 ng/mL indicates vitamin D deficiency.

It is considered that vitamin D deficiency is common among athletic populations, especially those who reside in northern latitudes. Using recreational athletes as their sample cohort, Close *et al.* (2013) found that 57 percent of them were vitamin D deficient at baseline (20.4 ± 9.6 ng/mL). It is recommended that athletes with vitamin D deficiency consider vitamin D supplementation. A recent review indicated that blood levels of 25-hydroxyvitamin D greater than 30 ng/mL were associated with reduced muscle pain and inflammation and increased muscle protein synthesis, adenosine triphosphate levels, strength, power, and physical performance (Shuler *et al.* 2012).

Vitamin E

Vitamin E refer to eight different naturally occurring compounds that all have somewhat similar chemical structure. Of these, α-tocopherol is the most biologically active. Vitamin E was initially identified as a fat-soluble component of grains that was necessary for fertility in laboratory rats. In fact, the name tocopherol was derived from the Greek *tokos* (childbirth) and *phero* (to bear) and means "to bring forth offspring." However, vitamin E is now known to have many other functions. For example, its potential for decreasing risk of chronic diseases such as heart disease has attracted much public interest.

Vitamin E is widespread in foods. Much of the vitamin E in the diet comes from vegetable oils and products made from them, such as margarine and salad dressings (Table 5.5). Wheat germ oil is especially rich in vitamin E. Some dark green vegetables such as broccoli and spinach contain vitamin E as well. Vitamin E can be easily destroyed during food preparation, processing, and storage. Therefore, fresh or lightly processed foods are preferable sources. Most processed and convenience foods do not contribute enough vitamin E to ensure an adequate intake. Absorption of vitamin E occurs in the small intestine and requires the presence of bile and the synthesis of micelles. Vitamin E is circulated in chylomicrons via the lymph and, in the blood, eventually reaches the liver. In the liver, vitamin E is repackaged into VLDLs for further delivery in the body. Excess vitamin E is stored mainly in adipose tissue.

Like the carotenoids, vitamin E acts as an antioxidant preventing oxidation and **free radical** damage. Much of the body's vitamin E is associated with various membranes. Recall that cell membranes consist of a bilayer of phospholipid. In addition, many cell organelles, such as mitochondria and endoplasmic reticula, are enclosed in a phospholipid bilayer membrane. Maintaining these membranes is vital to the stability and function of cells and their organelles, and vitamin E plays a major role. Specifically, it protects the fatty acids in the membrane from free radical-induced oxidative damage

Table 5.5 Food sources of vitamin E

Food item	*Amount*	*Vitamin E content (mg)*
Total cereal	3/4 cup	22.5
Sunflower oil	2 tablespoons	16.3
Sunflower seeds	1 ounce	14.3
Safflower oil	1 tablespoon	5.9
Canola oil	1 tablespoon	5.7
Almonds	1 ounce	4.5
Italian dressing	2 tablespoons	3.1
Mayonnaise	1 tablespoon	3.0
Avocado	1 med	2.7
Peanut butter	2 tablespoons	2.4
Peanuts	1 ounce	2.1
Kiwi	2 med	1.8
Eggs	2 large	1.6
Salmon	3 ounces	1.2
Margarine	1 teaspoon	1.2
Apricots	2 med	0.8
Chicken	3 ounces	0.7
Carrots, cooked	1/2 cup	0.6
Wholewheat bread	2 slices	0.5
Orange	1 med	0.4
Raw tomato	1/2 cup	0.3
2% milk	1 cup	0.2
Cheddar cheese	1.5 ounces	0.2
Oatmeal	1 cup	0.2

Note
RDA: 15 mg/day for both men and women.

(Figure 5.2). This occurs because vitamin E can donate electrons to free radicals, making them more stable. This protection is especially important in cells that are exposed to oxygen, such as those in the lungs and red blood cells. Vitamin E can also defend cells from damage by heavy metals, such as lead and mercury, and toxins, such as carbon tetrachloride, benzene, and a variety of drugs. It also protects against some environmental pollutants such as ozone. The ability of vitamin E to act as an antioxidant is enhanced in the presence of other antioxidant micronutrients, such as vitamin C (as shown in Figure 5.2). Because polyunsaturated fats are particularly susceptible to oxidative damage, the vitamin E requirement increases as polyunsaturated fat intake increases.

Because antioxidant nutrients protect DNA from cancer-causing free radical damage, people are very interested in the possibility that vitamin E may prevent or cure cancer risk. However, although diets high in vitamin E are associated with decreased cancer risk, there is little experimental evidence that vitamin E by itself decreases the risk of this disease (Bostick *et al.* 1993, Graham and McLean 1992, Kline *et al.* 2004). As an antioxidant, vitamin E also helps protect LDL cholesterol from oxidation, which can lead to atherosclerosis. It may also inhibit an enzyme that allows the build-up of atherosclerotic plaque and increases the synthesis of an enzyme needed to produce eicosinoids that help lower blood pressure and reduce blood clot formation (Steiner 1999, Emmert and Kirchner 1999). At this moment in time, experts do not know whether mega-dose vitamin E supplements taken by otherwise healthy people confer any more protection against cardiovascular disease and cancer than that achieved by improving diet, performing regular physical activity, not smoking, and maintaining a healthy body weight. In

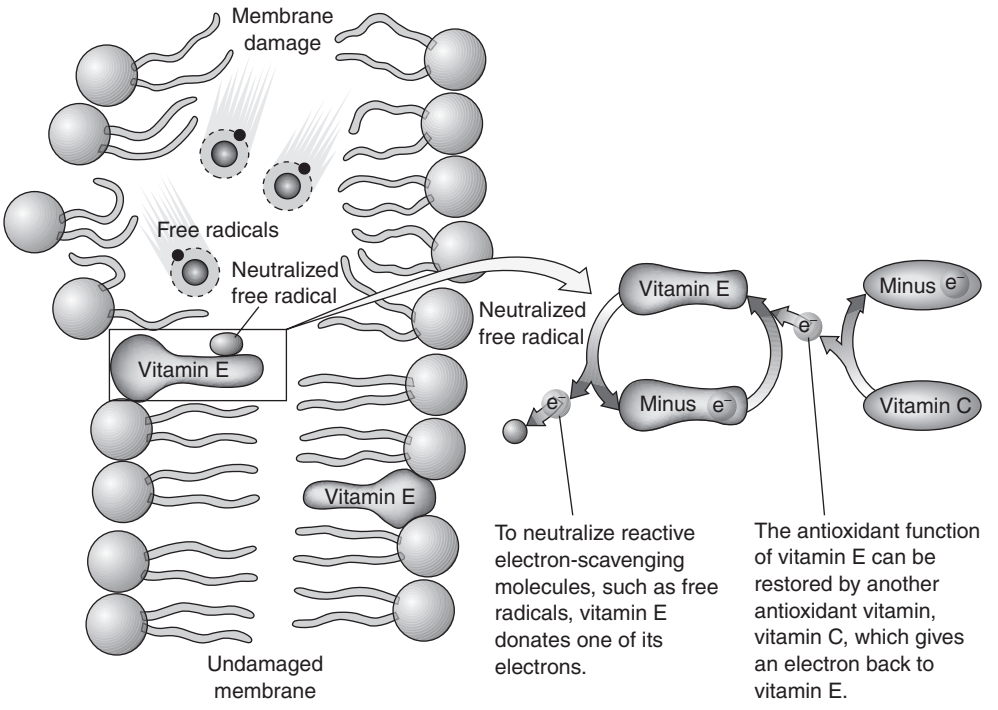

Figure 5.2 Vitamin E functions as an antioxidant that protects the unsaturated fatty acids in cell membranes by neutralizing free radicals

Source: Smolin and Grovenor (2010). Used with permission.

fact, the American Health Association considers that it is premature to recommend vitamin E supplements to the general public based on current knowledge and the failure of major clinical trials to show any benefit. In addition, the FDA has denied the request of the supplement industry to make a health claim that vitamin E supplements reduce the risk of cardiovascular disease and cancer.

Whether athletes and physically active individuals should supplement vitamin E or other antioxidants also remains open to debate. Moderate- to high-intensity endurance training can increase antioxidant enzyme activity, as well as reduce markers for exercise-induced oxidative stress (Miyazaki *et al.* 2001). However, very high training loads, such as ultra-marathons and ironman triathlons, are associated with an acute reduction in antioxidant capacity and an increase in markers of oxidative stress (Neubauer *et al.* 2008). A topic of much discussion in this area is whether the use of supplements may compromise natural physiological processes. Some researchers contend that antioxidant supplementation may interfere with the cellular signaling function of reactive oxygen species and therefore prevent the adaptations that are necessary for performance improvements (Gross *et al.* 2011). **Reactive oxygen species** are chemically reactive molecules containing oxygen, such as peroxides and superoxides, and have important roles in cell signaling and homeostasis. For athletes and physically active individuals, a higher than normal antioxidant intake can help maintain a normal pro-oxidant/antioxidant balance. However, this increased intake should ideally be achieved by using mixed and balanced diets high in antioxidants rather than by simply taking antioxidant supplementation in large doses.

Vitamin E deficiency is uncommon, and cases have only been reported in infants fed with formula that contain inadequate vitamin E, people with genetic abnormalities, and in diseases causing malabsorption of fat. Vitamin E deficiency is characterized by a variety of symptoms, including neuromuscular problems, loss of coordination, and muscular pain. Vitamin E deficiency also causes membranes of red blood cells to weaken and rupture, a condition referred to as hemolytic anemia. This is because vitamin E is especially important in protecting red blood cells from oxidative damage. Hemolytic anemia reduces the blood's ability to transport oxygen, resulting in weakness and fatigue.

The RDA for vitamin E for adult males and females is set at 15 mg per day. This value is based on the amount needed to maintain plasma concentrations of α-tocopherol that protect red blood cells from breaking. The RDA for vitamin E does not change regardless of age or pregnancy status, although a slight increase is recommended for women who are lactating. The upper level for vitamin E for a healthy population is 1000 mg per day of supplemental α-tocopherol. This upper level was established because excessive amounts of vitamin E can reduce blood clotting by interfering with the action of vitamin K.

Vitamin K

Vitamin K was discovered and named for its role in koagulation ("coagulation" in Danish) by Henrik Dam, a Danish physiologist who found that vitamin K deficiency in chickens caused excessive bleeding. Dam received a Noble Prize in physiology or medicine in 1943 for this discovery. As with all the fat-soluble vitamins, vitamin K is found in several forms. Phylloquinone is the form found in plants and the primary form in the diet. A group of vitamin K compounds, called menaquinones, are found in fish oils and meats, and are synthesized by bacteria, including those in the human intestine. Menaquinones are also the form found in vitamin K supplements. Only a small number of foods provide significant amounts of vitamin K. Liver, fish, legumes, and leafy green vegetables such as spinach, broccoli, Brussels sprouts, kales, and turnip greens provide about half of the vitamin K in a typical North American diet (Table 5.6). Some vegetable oils are also good sources. Some of the vitamin K produced by bacteria in the human gastrointestinal tract is also absorbed. Dietary vitamin K is absorbed, along with other fat-soluble vitamins in the small intestine via micelle. Vitamin K is then incorporated into chylomicrons and put into lymph, eventually entering the blood. Vitamin K produced by bacteria in the large intestine is transported into epithelial cells by simple diffusion and then circulated to the liver via blood. The liver packages both dietary and bacterially produced forms of vitamin K into lipoproteins for delivery to the rest of the body.

Vitamin K is needed for the production of the blood-clotting protein prothrombin and other specific blood-clotting factors. These proteins are needed to produce fibrin, the protein that forms the structure of the blood clot (Figure 5.3). Injuries as well as the normal wear and tear of daily living produce micro tears in blood vessels. To prevent blood loss, these tears must be repaired with blood clots. Other roles for vitamin K are less well understood. It has been suggested that vitamin K also catalyzes the carboxylation of other proteins needed for bone and tooth formation. Only after they have been carboxylated can these proteins bind calcium. Some studies have shown that consuming foods high in vitamin K is associated with decreased risk for hip fracture (Booth *et al.* 2004, Radecki 2005, Sasaki *et al.* 2005). However, further studies are needed to determine whether increasing vitamin K intake results in increased bone strength.

Although rare in healthy adults, vitamin K deficiency appears in some infants and people with diseases that cause lipid malabsorption. In addition, the prolonged use of

Table 5.6 Food sources of vitamin K

Food item	*Amount*	*Vitamin K content (μg)*
Kale, cooked	1/2 cup	530
Turnip green, cooked	1 cup	520
Spinach, cooked	1 cup	480
Brussel sprouts, cooked	1/2 cup	150
Spinach, raw	1 cup	144
Asparagus, cooked	1 cup	144
Broccoli, cooked	1/2 cup	110
Lettuce	1 cup	97
Green beans, cooked	1/2 cup	49
Cabbage, raw	1 cup	42
Kiwi	2 med	38
Green peas	1/2 cup	26
Soybean oil	1 tablespoon	25
Cauliflower, cooked	1 cup	20
Carrots, cooked	1/2 cup	18
Canola oil	1 tablespoon	17
Tomato, raw	1/2 cup	3
Wholewheat bread	2 slices	2

Note
RDA: 120 μg/day for men and 90 μg/day for women.

antibiotics can kill the bacteria that normally live in the large intestine, resulting in vitamin K deficiency. The main sign of vitamin K deficiency is excessive bleeding. In infants, there is little transfer of this vitamin from mother to fetus, and because the infant gut is free of bacteria, none is made there. Further, breast milk is low in vitamin K. Therefore, to prevent uncontrolled bleeding, infants are typically given a vitamin K injection within six hours of birth.

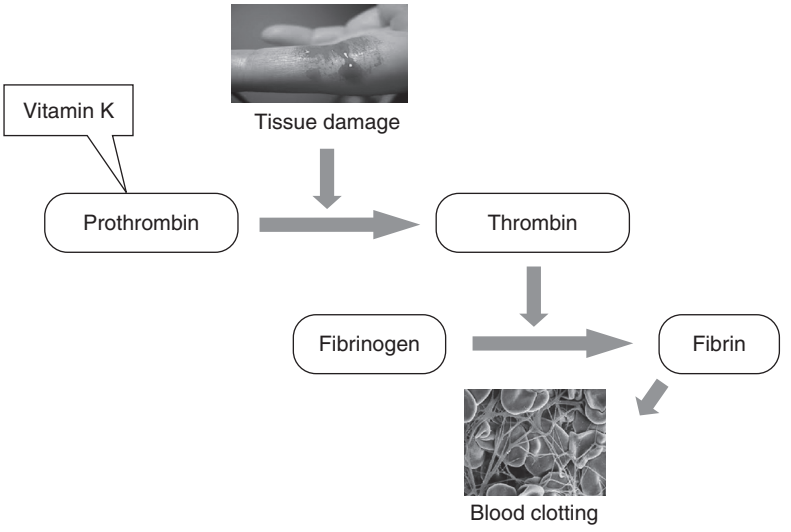

Figure 5.3 The role of vitamin K in the blood-clotting process

Unlike other fat-soluble vitamins, vitamin K is used rapidly by the body, so a constant supply is necessary. The RDA for vitamin K has been set at about 120 µg a day for men and 90 µg a day for women. Additional vitamin K is provided by bacteria in the gastrointestinal tract. The RDA is not increased for pregnancy or lactation, and remains unchanged with advancing age. Oral vitamin K supplementation generally poses no risk of toxicity, so no upper level has been established. Because vitamin K functions in blood clotting, high doses can interfere with anticoagulant drugs used to lessen blood clotting. Therefore, those who are prescribed these medications should consult their physicians before taking supplements containing vitamin K.

Water-soluble vitamins

Water-soluble vitamins include vitamin C and the B vitamins such as thiamin, riboflavin, niacin, pantothenic acid, biotin, vitamin B-6, folate, and vitamin B-12. They dissolve in water, so large amounts of these vitamins can be lost during food processing and preparation. Vitamin content is best preserved by light cooking methods, such as stir-frying, steaming, and microwaving. Water-soluble vitamins are absorbed mostly in the small intestine, and to a lesser extent the stomach. The extent to which vitamins are absorbed and used in the body, or bioavailability, is influenced by many factors, including nutritional status, other nutrients and substances in foods, medications, age, and illness. Once absorbed, the water-soluble vitamins are circulated to the liver in the blood. Because the body does not store large quantities of most water-soluble vitamins, they generally do not have toxic effects when consumed in large amounts. Most water-soluble vitamins are readily excreted from the body with an excess generally ending up in the urine and stool and very little being stored. Most B vitamins function as coenzymes that help regulate energy metabolism, as illustrated in Figure 5.4, whereas vitamin C may be best known for its role in the synthesis and maintenance of connective tissues as well as in preventing scurvy. The following is a more detailed discussion for each of the water-soluble vitamins presented separately.

Thiamin (vitamin B1)

Thiamin or vitamin B1 is widely distributed in foods. A large proportion of the thiamin consumed in the United States comes from enriched grains used in foods such as breakfast cereals and baked goods (Table 5.7). Pork, wholegrains, legumes, nuts, seeds, and organ meats (e.g., liver, kidney, heart) are also good sources. The adult RDA for thiamin is 1.1 and 1.2 milligrams per day. The RDA is based on the amount of thiamin needed to achieve and maintain normal activity of a thiamin-dependent enzyme found in red blood cells and normal urinary thiamin secretion. For an average adult, half of the thiamin may be obtained from 4 oz of pork or 3 cups of soy milk.

Thiamin does not provide energy, but it is important in the energy-producing reactions in the body. Thiamin functions as a coenzyme in reactions in which carbon dioxide is lost from large molecules. For example, the reaction that forms acetyl CoA from pyruvate requires thiamin pyrophosphate, an active form of thiamin. Thiamin is therefore essential to the production of energy from glucose. Thiamin is also needed for the synthesis of the neurotransmitter acetylcholine and production of sugar ribose, which is needed to synthesize ribonucleic acid (RNA).

The thiamin deficiency disease is called beriberi, a word that means “I can’t” in the Sri Lanka language of Sinhalese. The symptoms include weakness, loss of appetite, irritability, nervous tingling throughout the body, poor arm and leg coordination, and deep muscle pain in the calves. A person with beriberi often develops an enlarged heart and sometimes severe edema.

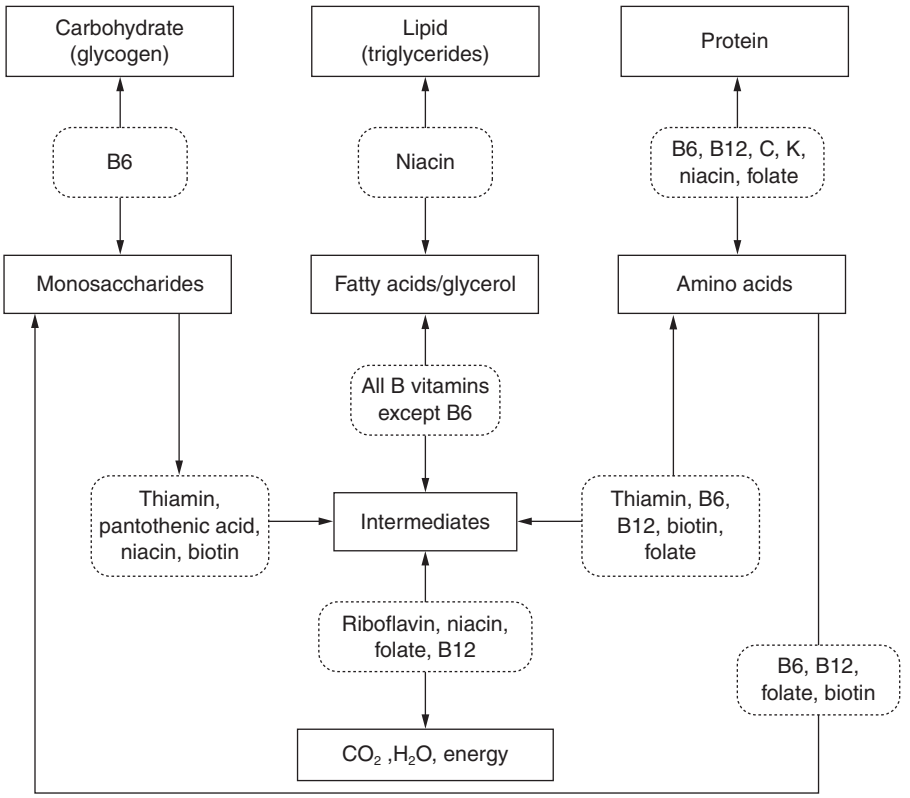

Figure 5.4 Various roles which water-soluble vitamins play in metabolic pathways

Source: Wardlaw and Smith (2013). Used with permission.

Riboflavin (vitamin B2)

Riboflavin or vitamin B2 consists of a multi-ring structure attached to the simple sugar ribose. Riboflavin in the body is typically found as one of its coenzymes, flavin adenine dinucleotide (FAD), and is important for energy metabolism. Milk is the best source of riboflavin in the North American diet (Table 5.7). Other major sources include liver, red meat, poultry, fish, and wholegrains and enriched breads and cereals. Vegetable sources include asparagus, broccoli, mushrooms, and leafy green vegetables such as spinach. The RDA for riboflavin for adult men and women are 1.3 mg per day and 1.1 mg per day, respectively. Additional riboflavin is recommended during pregnancy to support growth and increased energy utilization. Two cups of milk provide about half the amount of riboflavin recommended for a typical adult. Although riboflavin is relatively stable during cooking, it is easily destroyed by exposure to light. For this reason, milk is packaged in cardboard or cloudy plastic containers, and it is recommended that food be stored in dark containers or covered with paper or foil.

The coenzyme forms of riboflavin participate in many energy-yielding metabolic pathways. When cells generate energy using oxygen-requiring pathways, such as when fatty acids are broken down and burned for energy, the coenzymes of riboflavin are used. Riboflavin is also required for the synthesis of other compounds. For example, it is

Table 5.7 A summary of water-soluble vitamins

Vitamin	*Sources*	*RDA for adults*	*Major functions*	*Deficiency diseases and symptoms*
Thiamin (B1)	Enriched grains, pork, wholegrains, legumes, nuts, seeds, organ meats	1.1–1.2 mg	Coenzyme in acetyl-CoA formation, Krebs cycle, nerve function	Beriberi: tingling, poor coordination, weakness, heart changes
Riboflavin (B2)	Milk, leafy greens, enriched grains, poultry, fish	1.1–1.3 mg	Coenzyme in Krebs cycle, fat metabolism, electron transport chain	Inflammation of the mouth and tongue, dermatitis
Niacin (B3)	Enriched grains, peanuts, poultry, beef, tuna	14–16 mg	Coenzyme in glycolysis, Krebs cycle, electron transport chain	Pellagra: dementia, diarrhea, and dermatitis
Pantothenic acid	Meat, seeds, mushrooms, peanuts, eggs	5 mg*	Coenzymes in Krebs cycle, fat metabolism	Tingling in the feet and legs, fatigue, weakness, nausea
Biotin (B7)	Cauliflower, egg yolks, peanuts, liver, cheese	30 μg	Coenzyme in glucose production, fat synthesis	Depression, hallucinations, skin irritations, inflections, poor muscle control
Vitamin B6	Meat, legumes, seeds, leafy greens, whole grains	1.3–1.7 mg	Coenzyme in protein metabolism, neurotransmitter and hemoglobin synthesis	Headache, nausea, poor growth, microcytic hypochromic anemia
Folate (Folic acid)	Leafy greens, organ meats, legumes, orange juice, milk,	400 μg DFE†	Coenzyme in DNA synthesis and amino acid metabolism	Macrocytic anemia, diarrhea, poor growth, neural tube defects
Vitamin B12	Meat, milk, poultry, seafood, eggs, organ meats	2.4 μg	Coenzyme in folate metabolism, nerve function	Pernicious anemia, poor nerve function
Vitamin C	Citrus fruits, green peppers, cauliflower, broccoli, strawberries	75–90 g	Collagen synthesis, hormone and neurotransmitter synthesis, antioxidant	Scurvy: poor wound healing, bleeding gums, bruising, depression, hysteria

Notes
* Adequate intake (AI).
† Dietary folate equivalent

needed to convert vitamin A and folate (a B vitamin) into their active forms, convert tryptophan (an amino acid) into niacin (a B vitamin), and form vitamins B6 and K. Riboflavin is also involved in the metabolism of some important neurotransmitters, such as dopamine, and in several important reactions that protect biological membranes from oxidative damage.

The symptoms associated with riboflavin deficiency include inflammation of the mouth and tongue, dermatitis, cracking of tissue around the corners of the mouth, various eye disorders, and sensitivity to the sun. These symptoms usually develop after approximately two months of a riboflavin-poor diet. A deficiency of riboflavin is rarely seen alone. Instead, it often occurs with deficiencies of other B vitamins such as niacin, thiamin, and vitamin B-6 because these nutrients regularly occur in the same foods.

Niacin (vitamin B3)

Niacin or vitamin B3 takes two forms: nicotinic acid and nicotinamide. The body uses both forms to make the coenzymes nicotinamide adenine dinucleotide (NAD) and nicotinamide adenine dinucleotide phosphate (NADP). NAD and NADP are involved in numerous reactions in the body, many of which are required for energy metabolism. Major sources of niacin are poultry, ready-to-eat breakfast cereals, beef, wheat bran, tuna, and other fish, asparagus, and peanuts (Table 5.7). Coffee and tea also contribute some niacin to the diet. Niacin is heat stable, and little is lost in cooking. Niacin can be synthesized from essential amino acid tryptophan. If a diet that contains high-protein foods such as milk and eggs, which are poor sources of niacin but good sources of tryptophan, much of the need for niacin is met by tryptophan. However, this happens only if enough tryptophan is available to meet the needs of protein synthesis. The adult RDA of niacin is 14 to 16 mg per day. The RDA is expressed as niacin equivalents to account for niacin received from the diet as well as that made from tryptophan.

Niacin is important in the production of energy from energy-yielding nutrients as well as in reactions that synthesize other molecules. As mentioned earlier, the body uses niacin to make the two active coenzymes nicotinamide adenine dinucleotide (NAD) and nicotinamide adenine dinucleotide phosphate (NADP). NAD functions in glycolysis and the Krebs cycle, accepting released electrons and passing them to the electron transport chain where ATP is formed. NADP acts as an electron carrier in reactions that synthesize compounds, including fatty acids, cholesterol, steroid hormones, and DNA. Niacin has additional functions unrelated to its role as a coenzyme. For example, it is important for maintaining, replicating, and repairing DNA, and may play a role in protein synthesis, glucose homeostasis, and cholesterol metabolism. It has been shown that consuming large amounts of niacin (2 to 4 g/day) lowers low-density lipoprotein (LDL) cholesterol and increases high-density lipoprotein (HDL) cholesterol (Ganji *et al.* 2003, Krauss 2004).

Almost every cellular metabolic pathway uses niacin as a coenzyme, so a deficiency causes widespread changes in the body. The group of niacin deficiency symptoms is known as pellagra, which means rough and painful skin. The early symptoms of the disease include poor appetite, weight loss, and weakness. If left untreated, they can then result in dementia, diarrhea, and dermatitis (especially on areas of skin exposed to the sun). Pellagra is the only dietary deficiency disease ever to reach epidemic proportions in the United States. It became a major problem in the southeastern United States in the late 1800s and persisted until the late 1930s when standards of living and diets improved. Today, pellagra is rare in Western societies, but may still be seen in the developing world.

Pantothenic acid (vitamin B5)

Pantothenic acid or vitamin B5 is a nitrogen-containing vitamin named for the Greek word *pantos*, meaning "everywhere." This is because pantothenic acid is found in almost every plant and animal tissue. Pantothenic acid functions as a component of coenzyme A (CoA) in a variety of metabolic reactions. Rich sources of pantothenic acid are sunflower seeds, mushrooms, peanuts, and eggs (Table 5.7). Other sources are meat, milk, and many vegetables. There is not enough information to establish RDAs for pantothenic acid; an adequate intake (AI) set for pantothenic acid is 5 mg per day for adults. Because no evidence exists of toxicity, no upper limits are set for this vitamin as well.

The primary function of pantothenic acid as CoA is in the metabolism of glucose, amino acids, and fatty acids for energy (ATP) production via glycolysis and the Krebs cycle. For example, one of the pivotal steps in energy metabolism involves converting pyruvate into acetyl-CoA. This reaction requires pantothenic acid. The ability to produce acetyl CoA is essential for the body to metabolize energy-yielding nutrients for ATP production. Pentothenic acid is also required for synthesizing many other critical compounds in the body, including heme (a portion of hemoglobin), cholesterol, bile salts, phospholipids, fatty acids, and steroid hormones.

Because it is found in almost all foods, pantothenic acid deficiency is rare. Nonetheless, a condition called "burning feet syndrome" is thought to be due to severe pantothenic acid deficiency. Burning feet syndrome causes a tingling in the feet and legs as well as fatigue, weakness, and nausea. A deficiency in pantothenic acid may also occur when alcoholism is accompanied by a nutrient-deficient diet. However, the symptoms would probably be hidden among deficiencies of thiamin, riboflavin, vitamin B6, and folate, so that pantothenic acid deficiency may be unrecognizable.

Biotin (vitamin B7)

Biotin or vitamin B7 is a sulfur-containing molecule with two connected ring structures and a side chain. The body obtains biotin from both the diet and via biotin-producing bacteria in the large intestine. Cauliflowers, egg yolks, peanuts, and cheese are good sources of biotin (Table 5.7). Food containing raw egg whites should be avoided not only because a protein in egg white, called avidin, binds biotin and prevents its absorption, but because raw eggs may also be contaminated with bacteria that can cause bloodborne illness. Cooking eggs thoroughly destroys bacteria and denatures avidin so that it cannot bind biotin. No RDA is available for this vitamin. However, AI for biotin has been set to be 30 μg per day for adults. Biotin is relatively nontoxic. Therefore, no upper limit for biotin has been set.

Biotin acts as a coenzyme for several enzymes, all of which catalyze carboxylation reaction. In other words, each biotin-requiring enzyme causes the acid group COOH to be added to a molecule. In general, these enzymes are involved in energy metabolism pathways. For example, a biotin-requiring enzyme converts pyruvate into oxaloacetate, a key step in gluconeogenesis. Biotin is also a coenzyme for reactions that allow the body to use some amino acids in the Krebs cycle, for the synthesis of fatty acids, and for the breakdown of the amino acid leucine. In addition to biotin's role as a coenzyme, it has non-coenzyme functions related to gene expression, especially that influencing cell growth and development.

Although biotin deficiency is uncommon, it occurs in small portions of the population, such as people who routinely consume large quantities of raw egg whites. However, in theory it would take daily consumption of at least 12 raw egg whites for a prolonged period of time to cause biotin deficiency. Biotin may also be caused by conditions

impairing intestinal absorption such as inflammatory bowel disease. Signs and symptoms of biotin deficiency include depression, hallucinations, skin irritations, inflections, hair loss, poor muscle control, seizures, and developmental delay in infants.

Vitamin B6

Almost all the B vitamins discussed so far have a common role of functioning as a coenzyme involved in energy production. Vitamin B6, however, is somewhat unique in that it is mainly involved in protein and amino acid metabolism. There are three forms of vitamin B6 – pyridoxine, pyridoxal, and pyridoxamine – all made of a modified, nitrogen-containing ring structure. All three forms can be changed to the active vitamin B6 coenzyme involved in numerous chemical reactions. Major sources of vitamin B6 are animal products, ready-to-eat breakfast cereals, potatoes, and milk (Table 5.7). Other sources are fruits and vegetables such as bananas, cantaloupes, broccoli, and spinach. Overall, animal sources and fortified products are the most reliable because the vitamin B6 they contain are more absorbable than that in plant foods. The adult RDA of vitamin B6 is 1.3 to 1.7 mg per day. Vitamin B6 is easily destroyed in processing such as heating and freezing. It is not one of the vitamins added to "enrich" products, but fortified breakfast cereals make an important contribution to vitamin B6 intake.

Vitamin B6 comprises a group of compounds including pyridoxine, pyridoxal, and pyridoxamine as mentioned above. All three forms can be converted into the active coenzyme form, pyridoxal phosphate. Pyridoxal phosphate is needed for the activation of more than 100 enzymes involved mainly in protein and amino acid metabolism. As shown in Figure 5.5, vitamin B6 is used to synthesize nonessential amino acids by transamination and to remove the amino group, so amino acids may be used to produce energy or to synthesize glucose. This vitamin is also needed to remove the carboxyl group (COOH) from amino acids for the synthesis of neurotransmitters such as serotonin and dopamine as well as hemoglobin. Without pyridoxal phosphate, the non-essential amino acids cannot be synthesized. Recall that only 9 essential amino acids must be obtained from foods, whereas 20 amino acids are needed for life. Without vitamin B6, all 20 amino acids would be essential. Pyridoxal phosphate is important for the immune system because it is needed to form white blood cells. It is also needed for the synthesis of the lipids that are part of the myelin coating on nerves.

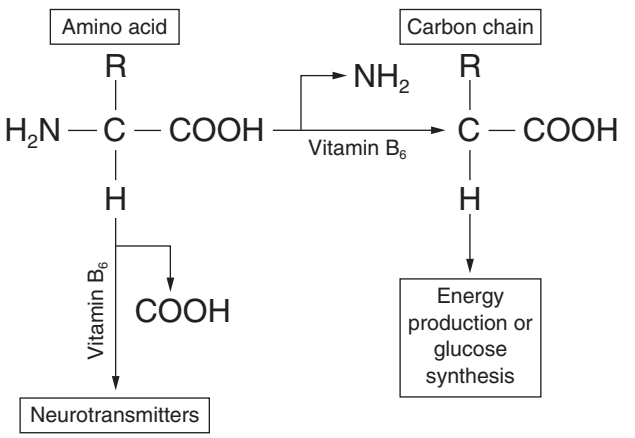

Figure 5.5 The role of vitamin B6 in protein metabolism, synthesis of neurotransmitters, and energy production

Vitamin B6 deficiency results in inadequate heme production, and thus lower concentrations of hemoglobin in red blood cells. This condition, called **microcytic hypochromic anemia**, results from the fact that red blood cells are small in size and light in color. It decreases oxygen availability in tissues and impairs the ability to produce ATP via aerobic metabolism. Vitamin B6 deficiency also causes neurological symptoms, including depression, headaches, confusion, numbness and tingling in the extremities, and seizures. These symptoms may be related to the role of vitamin B6 in neurotransmitter synthesis and myelin formation. Other deficiency symptoms such as poor growth, skin lesions, and decreased antibody formation may occur because vitamin B6 is important in protein and energy metabolism. Since vitamin B6 is needed for amino acid metabolism, the onset of deficiency can be hastened by a diet that is low in vitamin B6 but high in protein.

Folate

Folate consists of three parts: (1) a nitrogen-containing double-ring structure; (2) a nitrogen-containing single-ring structure, and (3) a glutamic acid (also called glutamate). Folate typically has additional glutamic acids attached to it. The inter-conversion of these "polyglutamate" forms of folate is important for functions of folate. Folic acid, which is the oxidized and stable form of folate, is rarely found in foods but is used in vitamin supplements and food fortification. Folate is derived from the Latin word *folium*, which means foliage or leaves. Green, leafy vegetables as well as organ meats, sprouts, legumes, and orange juice are the richest sources of folate. In addition, ready-to-eat cereals, milk, and bread are also important sources of folate (Table 5.7). Folate is susceptible to destruction by heat. Food processing and preparation can destroy at least half of the folate in food. This underscores the importance of eating fresh fruits and raw or lightly cooked vegetables regularly.

Recommendations concerning folate intake have received substantial attention since its relationship with neural tube defects was determined in the late 1980s. The adult RDA for folate is set at 400 µg of dietary folate equivalents (DFEs) per day. One DFE is equal to 1 µg of food folate or 0.5 µg of synthetic folic acid consumed on an empty stomach. In order to reduce the risk of neural tube defects, a special recommendation is made for women capable of becoming pregnant. A daily intake of 400 µg of synthetic folic acid from fortified foods and/or supplements is recommended, in addition to the food folate consumed in a diet. The RDA for folate during pregnancy is increased to 600 µg per day due to the increase in cell division. Although this level may be met by a carefully selected diet, folate is typically supplemented during pregnancy.

Folate acts as a coenzyme for many reactions, all involving the transfer of a single-carbon or methyl group such as –CH3. These reactions shift carbons from one molecule to another to form the many organic substances the body needs. An example of folate's single-carbon role is the conversion of homocysteine to the amino acid methionine. In this reaction, 5-methyltetrahydrofolate (an inactive form of folate) gives off a methyl group (–CH3) to homocysteine that produces methionine and tetrahydrofolate. This important reaction provides the body with the amino acid methionine as well as tetrahydrofolate, an active form of folate. However, this reaction does not happen by itself. Instead, it occurs in synchrony with another reaction involving vitamin B12. So, the production of methionine from homocysteine requires both folate and B12. Folate is also involved in single-carbon transfer reactions required to make purines and pyrimidines, the molecules that make up DNA and RNA. Because DNA must be synthesized each time a new cell is made, folate is essential for the growth, maintenance, and repair of all tissues in the body.

Folate-deficiency symptoms include poor growth, problems in nerve development and function, gastrointestinal deterioration, and anemia. Anemia results when folate is deficient because the bone marrow cells that develop into blood cells cannot divide. Instead, they just grow bigger. These large red blood cells, called macrocytes, are immature and have limited oxygen-carrying capacity. This type of anemia is also known as **macrocytic anemia**. Lack of ability for cells to divide due to folate deficiency also contributes to the deterioration of the gastrointestinal tract. This is because the cells that form the inner lining of the intestinal wall cannot successfully grow or be repaired. Folate supplementation has been considered necessary for preventing neural tube defects. Women during early pregnancy are recommended to take up to 800 µg per day of synthetic folic acid, in addition to food folate in order to reduce incidence of neural tube defects. It must be noted that neural tube defects are not true folate deficiency symptoms because not every pregnant woman with inadequate folate levels will give birth to a child with a neural tube defect. Instead, neural tube defects are probably due to a combination of factors that include low folate levels and a genetic predisposition.

Vitamin B12

Vitamin B12 is the last of the B vitamins to be discovered. It is also referred to as cobalamin due to the fact that it contains the trace element cobalt (Co) and several nitrogen atoms. Major sources of vitamin B12 include meat, milk, ready-to-eat breakfast cereals, poultry, seafood, and eggs (Table 5.7). Organ meats, especially liver, kidneys, and heart, are especially rich sources of vitamin B12. Vitamin B12 can also be made by bacteria, fungi, and algae but not by plants and animals. Micro-organisms in the human colon produce B12, but it cannot be absorbed. Vitamin B12 is not supplied by plant products unless they have been contaminated with bacteria, soil, insects, or other sources of vitamin B12, or have been fortified with vitamin B12. Diets that do not include animal products must include supplements or foods fortified with vitamin B12 in order to meet needs. The RDA of vitamin B12 for adults is 2.4 µg per day. On average, adults consumed two times of the RDA or more. Such overconsumption seems to be necessary because it is assumed that only 50 percent of the vitamin B12 ingested is absorbed.

Vitamin B12 participates as a coenzyme in only two reactions. One reaction catalyzes the production of succinyl CoA, an intermediate in the Krebs cycle. This reaction ultimately allows the body to use some amino acids and fatty acids for energy production. The other reaction catalyzes the conversion of homocysteine into the amino acid methionine as mentioned earlier. This reaction also regenerates the active forms of folate that function in DNA synthesis. Without adequate vitamin B12, homocysteine levels build up in the blood, and folate becomes "trapped" as its inactive 5-methyltetrahydrofolate form. Thus, folate deficiency symptoms appear. In this context, a deficiency in vitamin B12 can cause a secondary folate deficiency and its related symptoms such as macrocytic anemia.

Symptoms of vitamin B12 deficiency include an increase in blood homocysteine levels and a macrocytic anemia that is indistinguishable from that seen in folate deficiency. The symptoms also include numbness and tingling, abnormalities in gait, memory loss, and disorientation due to degeneration of the myelin that coats the nerves, spinal cord, and brain. If not treated, these neurological symptoms may eventually lead to paralysis and death. A severe deficiency in vitamin B12 can be caused by **pernicious anemia**, a condition in which the parietal cells of the stomach that produce intrinsic factors are damaged. Intrinsic factor is a protein that binds to vitamin B12

and allows the vitamin to be absorbed in the ileum of the small intestine. Only small portions of vitamin B12 can be absorbed without intrinsic factor. Vitamin B12 deficiency is especially common in the elderly population. This is due to a variety of factors, including inadequate vitamin B12 intake, decreased synthesis of intrinsic factor, and reduced stomach acid secretion.

Vitamin C (ascorbic acid)

Vitamin C appears to play a role in almost every physiological system. For example, it is important for immune, cardiovascular, neurological, and endocrine systems. This relatively simple compound can be made from glucose in all plants and most animals, but not in humans. Thus, for humans, vitamin C is considered an essential nutrient. Vitamin C is also referred to as ascorbic acid. Major sources of vitamin C are citrus fruits, green peppers, cauliflowers, broccoli, cabbages, strawberries, and romaine lettuce (Table 5.7). Potatoes, breakfast cereals, and fortified fruit drinks are also good sources of vitamin C. The adult RDA of vitamin C is 75 to 90 mg per day. Cigarette smokers need to add an extra 35 mg per day to the RDA because of the great stress on their lungs from oxygen and toxic by-products of cigarette smoke. Nearly all individuals likely meet their daily needs for vitamin C via a regular diet. Nevertheless, nutrition experts who advocate increased use of vitamin C often recommend an intake of about 200 mg per day. Still, this amount can be obtained by sufficient fruit and vegetable intake. Vitamin C is rapidly lost in processing and cooking as it is water soluble, and it is unstable in the presence of heat, iron, copper, or oxygen.

The most notable function of vitamin C is its role in synthesizing the protein **collagen**. This protein is highly concentrated in connective tissue, bone, teeth, tendons, and blood-vessels. It is important for healing wounds. Vitamin C increases the cross-connections between amino acids in collagen, greatly strengthening the structural tissues it helps form. Vitamin C also functions as an antioxidant. Antioxidants are substances that protect against oxidative damage, which is damage caused by reactive oxygen molecules. Reactive oxygen species such as free radicals can be generated by normal oxidation reactions inside the body or can come from environmental sources such as air pollution or cigarette smoke. Free radicals cause damage by removing electrons from DNA, proteins, carbohydrates, or unsaturated fatty acids. This results in unstable structure and function of these molecules. DNA damage is considered a major reason for the increase in cancer incidence that occurs with age. Damage to lipoproteins and lipids in membranes is also implicated in the development of atherosclerosis. Vitamin C is vital for the function of the immune system, especially for the activity of certain immune cells. Thus, disease states that increase the need for immune function can increase the need for vitamin C, possibly above the RDA. Due to such association between vitamin C and immunity, most individuals supplement their diets with vitamin C in order to combat the common cold. However, it remains questionable as to whether vitamin C works effectively against colds and other infections. Numerous well-designed, double-blind studies have failed to show mega doses of vitamin C to reliably prevent colds, though it seems to reduce the duration of symptoms.

Due to its role of being an antioxidant, supplementing vitamin C is often a topic of discussion among athletes and physically active individuals just like vitamin E as discussed earlier. However, contrary to common belief, studies have recently demonstrated that antioxidant supplementation may interfere with exercise-induced cell signaling in skeletal muscle fibers. In turn, such changes in cell signaling may potentially blunt or block adaptations to training. For example, Gomez-Cabrera *et al.* (2008) investigated

whether high doses of vitamin C affected adaptation to endurance exercise training using both an animal and human model. Interestingly, endurance performance and markers for mitochondrial biogenesis increased to a greater extent in animals treated with the placebo than animals treated with vitamin C. In the human experiment, changes in VO_2max did not differ significantly between the supplement ($1000\,mg{\cdot}day^{-1}$) and placebo groups. In another study with untrained and trained male participants, Ristow *et al.* (2009) demonstrated that four weeks of vitamin C ($1000\,mg{\cdot}day^{-1}$) and E ($400\,IU{\cdot}day^{-1}$) supplementation blunted training-induced increases in the mRNA expression of genes associated with mitochondrial biogenesis and endogenous antioxidant systems in skeletal muscle. Clearly, antioxidants may interfere with adaptations to exercise in humans, and high doses of vitamin C as well as vitamin E should be used with caution.

Vitamin C deficiency can cause a deadly condition called scurvy. Scurvy results in a multitude of signs and symptoms, including bleeding gums, skin irritations, bruising, and poor wound healing, many of which are due to inadequate collagen production. Without vitamin C, the bonds holding adjacent collagen molecules together cannot be formed and maintained. The psychological manifestations of scurvy include depression and hysteria. Although it used to be very common, the increased availability of fruits and vegetables has made this disease rare. Scurvy can develop in infants fed diets consisting exclusively of cow's milk, but this condition can be reversed by adding fruit juice to the infant diet. Scurvy may also occur in alcoholics and elderly individuals consuming nutrient-poor diets.

Summary

- Vitamins are carbon-containing compounds required by the body daily in small quantities.
- Vitamins do not provide energy directly, but many contribute to energy-yielding chemical reactions in the body and promote growth and development.
- We consume vitamins that are naturally present in foods, added to foods by fortification and enrichment, and contained in supplements.
- Vitamins are classified as either fat soluble or water soluble. The fat-soluble vitamins are vitamins A, D, E, and K, whereas B vitamins and vitamin C are water soluble. Vitamin D deficiency is linked not only to osteoporosis, but also to increased risk for developing cardiovascular disease, diabetes, muscle weakness and pain, cognitive impairment in older adults, and certain types of cancer.
- Absorption of fat-soluble vitamins requires an adequate consumption of fat in the diet.
- Vitamins A, C, E, and carotenoids, precursors to vitamin A, serve important protective functions as antioxidants, and diets containing these micronutrients can reduce the potential for tissue damage and protect against heart disease and cancer.
- As antioxidants may interfere with adaptations to exercise in humans, one should avoid supplementing vitamins C and E in a large dose.
- Excess fat-soluble vitamins accumulate in body tissues and can become toxic. However, excess water-soluble vitamins generally remain non-toxic as they can be excreted via urine.
- Most B vitamins, such as vitamin B1 (thiamin), vitamin B2 (riboflavin), vitamin B3 (niacin), vitamin B5 (pantothenic acid), vitamin B6, and vitamin B7 (biotin), function as coenzymes in reactions involved in the metabolism of carbohydrate, fat, and protein.

- The B vitamin folate and vitamin B12 share the similar role of regulating the synthesis of DNA, which is required for cells to divide. Therefore, deficiency in these vitamins can result in problems, such as anemia and neural tube defects.
- Vitamin C may be best known for its role in the synthesis and maintenance of connective tissues as well as in preventing scurvy.

Case study: choose a vitamin supplement wisely

John works the late shift in a local warehouse four days a week. John is also a full-time student, and a combination of taking a full course load at college and working late hours has created a lot of stress for him. John also plays intramural soccer and writes regularly for the college newspaper. His many commitments make it important that he does not become ill. Recently, one of his roommates suggested that he take vitamin supplements to help prevent colds, flu, and other illnesses. The special multivitamin product that he is interested in recommends taking three tablets daily for health maintenance and two tablets every three hours at the first sign of feeling ill. John looks at the Supplement Facts label on the bottle and finds that each tablet contains (as a percentage of daily value): 35 percent for vitamin A (three-quarters is pre-formed vitamin A), 500 percent for vitamin C, 50 percent for zinc, and 20 percent for selenium. A monthly supply costs about $60.

Questions

- How many tablets should be taken per day if John was feeling ill?
- Given that the daily value for vitamin A is 1000 µg, what is the total amount of vitamin A in this larger dose?
- How is this amount compared with the upper level of 3000 µg for pre-formed vitamin A?
- How does the cost of this supplement compare to that of a typical multivitamin/mineral supplement available at your local drug store?

Review questions

1 What is a vitamin?
2 Why is the risk of toxicity greater with the fat-soluble vitamins than with water-soluble vitamins in general?
3 What do enrichment and fortification mean?
4 How would you determine which fruits and vegetables displayed in your supermarket are likely to provide plenty of antioxidants?
5 The need for certain vitamins increases as energy expenditure increases. Name two such vitamins and explain why this is the case.
6 Why is a low folate intake of particular concern for women of pregnancy or childbearing age?
7 Define the term "nutrient bioavailability."
8 Deficiencies in vitamins B6, B9, and B12 have been implicated for dementia. Explain the underlying causes.
9 Why will vitamin C deficiency cause poor wound healing?
10 Define the term "free radicals"; also identify sources of free radical sources.
11 Define the term "antioxidant"; also explain the role antioxidants play in the body.
12 Why is vitamin D considered unique? Describe health problems associated with vitamin D deficiency.
13 Define the terms "osteopenia" and "osteoporosis."

Suggested reading

1 American Dietetic Association (2005) Position of the American Dietetic Association: fortification and nutritional supplements. *Journal of the American Dietetic Association*, 105: 1300–1311.
This position statement from the American Dietetic Association (ADA) emphasizes that the best nutritional strategy for promoting optimal health and reducing the risk of chronic disease is to choose a wide variety of foods wisely, although they acknowledge that additional nutrients from fortified foods and/or supplements can help some people meet their nutritional needs.

2 Fletcher RH, Fairfield KM (2002) Vitamins for chronic disease prevention in adults: scientific review. *Journal of the American Medical Association*, 287: 3116–3126.
This article reviews the clinically important vitamins regarding their biological effects, food sources, deficiency syndromes, potential for toxicity, and relationship to chronic disease.

3 Voutilainen S, Nurmi T, Mursu J, Rissanen TH (2006) Carotenoids and cardiovascular health. *American Journal of Clinical Nutrition*, 83: 1265–1271.
Nutrition plays a significant role in the prevention of many chronic diseases such as CVD, cancers, and degenerative brain diseases. In this article, the role of main dietary carotenoids (i.e., lycopene, beta-carotene, alpha-carotene, beta-cryptoxanthin, lutein, and zeaxanthin) in the prevention of heart diseases is discussed.

Glossary

Bioavailability a measure of how well a nutrient can be absorbed and used by the body.

Collagen a fibrous protein found mainly in skin, bone, cartilage, tendons, teeth, and blood-vessels.

Enrichment a type of fortification in which nutrients are added for the purpose of restoring those lost in processing to the same or a higher level than originally present.

Fortification the process of adding specific nutrients to foods.

Free radical atoms or groups of atoms with an odd or unpaired number of electrons.

Macrocytic anemia a condition in which red blood cells grow bigger but are immature and have limited oxygen-carrying capacity.

Microcytic hypochromic anemia a condition in which blood cells are small in size and light in color due to lower concentrations in hemoglobin.

Osteoclasts types of bone cells that remove bone tissue.

Osteomalacia the softening of bone tissue due to vitamin D deficiency, an adult version of rickets.

Osteoporosis a chronic condition characterized by the demineralization of bone and a decrease in bone density and strength.

Pernicious anemia a decrease in red blood cells that occurs when the body cannot properly absorb vitamin B12 from the gastrointestinal tract.

Provitamins the vitamins that are available from foods in inactive forms, but once inside the body will be converted into active forms.

Reactive oxygen species chemically reactive molecules containing oxygen, such as peroxides and superoxides, and which have important roles in cell signaling and homeostasis.

Retinoids provitamin A compounds that include retinol, retinoic acid, and retinal.

Rickets inadequate bone mineralization due to vitamin D deficiency in infants and children who are in active stages of growth.

Vitamins organic compounds essential in the diet in small amounts to promote and regulate body functions necessary for growth, reproduction, and maintenance of the body.

Vitamin toxicity a condition in which a person develops symptoms as side effects from taking massive doses of vitamins.

6 Micronutrients

Minerals and water

Contents

Key terms

- Bone remodeling
- Cretinism
- Cupric
- Cuprous
- Cytochromes
- Extracellular fluid
- Ferric iron
- Ferrous iron
- Fluorosis
- Goiter
- Heme iron
- Hemoglobin
- Hydroxyapatites
- Hypertension
- Hypertonic
- Hypokalemia
- Hypotonic
- Interstitial fluid
- Intracellular fluid
- Iron deficiency anemia
- Isotonic
- Major minerals
- Myoglobin
- Non-heme iron
- Osmosis
- Osteoblasts
- Osteoclasts
- Osteopenia
- Specific heat
- Tetany
- Trace minerals

Minerals

In addition to organic molecules such as protein, carbohydrates, lipids, and vitamins, our bodies are also made up of inorganic matters. These inorganic substances include minerals and water, which together constitute over 60 percent of the body weight. Minerals are needed by the body as structural components and regulators of various biological processes. They make up the structure of our bones and teeth, and participate in hundreds of chemical reactions. The metabolic roles of minerals vary considerably. Some minerals, such as copper and selenium, work as co-factors, enabling various proteins, such as enzymes, to function. Minerals also contribute to many body compounds. For example, iron is a component of red blood cells. Sodium, potassium, and calcium aid in the transfer of nerve impulses throughout the body. Body growth and development also depend on certain minerals, such as calcium and phosphorous. Minerals may combine with other elements in the body, but they retain their chemical identity. Unlike vitamins, they are not destroyed by heat, oxygen, or acid. Minerals are divided into **major minerals**, or those needed in the diet in amounts greater than 100 mg per day or present in the body in amounts greater than 0.01 percent of the body weight, and **trace minerals**, or those required by the body in an amount of 100 mg or less per day or present in the body in an amount of 0.01 percent or less of body weight.

Dietary sources and bioavailability

Minerals in the diet come from both plant and animal sources. For example, iron is a component of muscle tissue, so it is found in meat, while magnesium is a component of chlorophyll, so it is found in leafy greens. In general, the quantities of most minerals in foods are quite predictable because minerals are regular components of the plant or animal. However, the amounts of some trace minerals in food may vary depending on the mineral concentration in the soil and water at the food's source. For example, the soil content of iodine is high near the ocean but usually quite low in inland areas. Therefore, foods grown near the ocean are better sources of iodine than those grown inland. The mineral content of foods can also be affected by food processing and refining. For example, when the skins of produce and bran and germ of grains are removed, many

trace elements, such as iron, selenium, zinc, and copper, are lost. Such food processing will also decrease the potassium content of foods. Some minerals are added inadvertently through contamination. For example, the iodine content of dairy products is increased by contamination from the cleaning solutions used in milking machines. Minerals can also be added intentionally. For example, the fortification of breakfast cereals can add calcium and other minerals. Choosing a variety of nutrient-dense foods including those that are unprocessed or less processed can help maximize the content of minerals in the diet.

Foods offer a plentiful supply of many minerals, but the ability of our body to absorb and use them varies. The bioavailability of minerals depends on many factors. Mineral ions that carry the same charge compete for absorption in the gastrointestinal tract. For example, calcium, magnesium, zinc, copper, and iron all carry 2^+ charge, and a high intake of one may reduce the absorption of others. Mineral bioavailability is also affected by the binding of minerals to other substances in the gastrointestinal tract. For example, spinach contains plenty of calcium, but only about 5 percent of it can be absorbed owing to the vegetable's high concentration of oxalate, a calcium binder. Components found in fibers, such as phytate, can also limit absorption of some minerals, such as calcium, magnesium, zinc, and iron, by binding to them. On the other hand, absorption of minerals can be facilitated by consuming several vitamins. For example, the active vitamin D improves calcium absorption. In addition, when consumed in conjunction with vitamin C, absorption of iron improves.

General functions of minerals

Minerals are transported in the blood bound to transport proteins. The binding of minerals to transport proteins helps regulate their absorption and prevent reactive minerals from forming free radicals that could cause oxidative damage to various tissues. Minerals function in a variety of ways in the body. For example, calcium and phosphorous are vitally important for the structure and strength of bones and teeth; iodine is a component of the thyroid hormones, which regulate metabolic rate; and chromium plays a role in regulating blood glucose levels. Many minerals participate in chemical reactions by serving as co-factors. They are also required for energy metabolism, nerve function, and muscle contraction. In addition, the electrolytes such as sodium and chloride, and potassium are essential for maintaining a proper fluid distribution across the body's different compartments.

Major minerals

Some of the general characteristics of minerals and how they function in the body have been discussed in proceeding sections. It appears that minerals serve three broad roles in the body: (1) providing structure in forming bones and teeth; (2) maintaining normal heart rhythm, muscle contractility, and neural conductivity; and (3) regulating metabolism by becoming constituents of enzymes and hormones. The following sections provide more detailed coverage of each of the major minerals, including sodium and chloride, potassium, calcium, phosphorus, magnesium, and sulfur.

Sodium and chloride

Sodium and chloride are almost always found together in foods, and in many ways have similar functions in the body. This is because they join via ionic bonds to form salt or sodium chloride (NaCl). These minerals are an essential part of our diets and add flavor

to our foods. Table salt is 40 percent sodium and 60 percent chloride. For example, dietary intake of 10 grams of salt translates into about 4 grams of sodium and 6 grams of chloride. About 80 percent of the sodium and chloride we consume is added to foods during food processing and cooking. A teaspoon of salt contains about 2 g (or 2000 mg) of sodium. Other food additives, such as monosodium glutamate, also contain sodium. In general, unprocessed foods such as fresh fruits and vegetables contain small amounts of sodium and chloride, whereas manufactured and highly processed foods like fast foods and frozen entrees contain large amounts. Some meats, dairy products, poultry, and seafood naturally contain moderate amounts of both sodium and chloride. We obtain these minerals also from salt-containing condiments, such as soy source and ketchup. The more processed and restaurant food one consumes, generally the higher one's sodium intake. Conversely, the more home cooking one does, the more sodium control that person has. Other foods that are especially high in sodium include salted snack foods, French fries, and potato chips, and sauces and gravies (Table 6.1).

Sodium and chloride, the most abundant ions in the blood, are the body's principal electrolytes. When the ionic bond of a NaCl molecule dissociates in water, sodium is released as a cation (Na^+), whereas chloride is released as an anion (Cl^-). Both ions play a major role in fluid balance. Because water moves naturally to areas that have high sodium and/or chloride concentrations, the body can maintain fluid balance by selectively moving these electrolytes where more water is needed. Diet high in salt can increase extracellular volume, including plasma volume. This may in turn cause high blood pressure or **hypertension.** A healthy blood pressure is 120/80 mmHg or less. However, hypertension is generally defined as a blood pressure of 140/90 mmHg or greater. Sodium is also important for nerve function and muscle contraction, both of which also involve potassium (K^+). In addition, chloride is needed for the production of hydrochloric acid (HCl) in the stomach, for removal of carbon dioxide (CO_2) by the lungs, and for optimal immune function.

The adequate intake of sodium for adults under age 51 is 1500 mg, and this number should be reduced by 100 to 200 mg for older adults. Under FDA food and supplement labeling rules, the daily value for sodium is 2400 mg or 2.4 grams. However, the amount typically eaten in North America ranges from 2300 to 4700 mg. If we ate only unprocessed foods and added no salt, we would consume about 500 mg of sodium per day. Nevertheless, the body really needs only about 200 mg per day to maintain physiological functions.

Deficiencies of sodium and chloride are rare in healthy individuals. However, they may occur in infants and small children who suffer diarrhea and/or vomiting. These conditions result in loss of sodium and chloride through the gastrointestinal tract or loss of nutrients before they even enter the intestine. Diarrhea and vomiting can be life threatening due to the rapid loss of both electrolytes and accompanying water. Less severe sodium and chloride deficiencies due to excessive sweating can occur in athletes, especially those involved in endurance sports such as marathon running. Symptoms of electrolytes deficiency include nausea, dizziness, muscle cramps, and, in severe cases, coma.

Potassium

Whereas sodium is the most abundant cation in the extracellular fluids, potassium (K) is the most abundant cation in the intracellular fluids. Potassium performs many of the same functions as sodium, such as fluid balance and nerve impulse transmission. However, it operates inside, rather than outside, of the cell. Intracellular fluids, those inside cells, contain 95 percent of the potassium in the body. Also unlike sodium, increasing potassium intake is associated with lower rather than high blood pressure.

Table 6.1 A summary of the major minerals

Vitamin	*Sources*	*RDA or AI**	*Major functions*	*Deficiency diseases and symptoms*
Sodium	Table salt, processed foods, condiments, sauces, soups, chips	Age 19–50 years: 1500 mg; age 51–70 years: 1300 mg; age >70 years: 1200 mg	Major positive ions of extracellular fluid, aids nerve impulse transmission, water balance	Muscle cramps, diarrhea, vomiting
Chloride	Table salt, processed foods, some vegetables	2300 mg	Major negative ions of extracellular fluid, used for acid production in stomach, aids nerve impulse transmission, water balance	Muscle cramps, diarrhea, vomiting
Potassium	Spinach, squash, bananas, orange juice, milk, meat, legumes, wholegrains	4700 mg	Major positive ions of intracellular fluid, aids nerve impulse transmission, water balance	Irregular heartbeats, muscle cramps, loss of appetite, confusion
Calcium	Dairy products, canned fish, leafy vegetables, tofu, fortified beverages and foods	Age 9–18 years: 1300 mg; age >18 years: 1000–1200 mg	Maintenance of bones and teeth, aids in nerve impulse transmission, muscle contraction, blood clotting	Stunted growth in children, increased risk of osteoporosis in adults, muscle cramps and, if extreme, muscle pain or tetany
Phosphorus	Dairy products, processed foods, fish, soft drinks, bakery goods, meats	Age 9–18 years: 1250 mg; age >18 years: 700 mg	Bone and tooth structure and strength, part of metabolic compounds, acid–base balance	Possibility of poor bone maintenance, muscle weakness
Magnesium	Wheat bran, green vegetables, nuts, chocolate, legumes	Men: 400–420 mg; women: 310–320 mg	Bone structure, aids enzyme function and energy metabolism, aids nerve and heart function	Weakness, muscle pain, poor heart function, confusion and, if extreme, convulsions
Sulfur	Protein foods	None	Parts of vitamins and amino acids, acid–base balance, aids in drug detoxification	None observed

Note
* Adequate intake (AI).

Generally, unprocessed foods are rich sources of potassium. These include fruits, vegetables, milk, wholegrains, dried beans, and meats. Major sources of potassium in the adult diet include milk, potatoes, beef, coffee, tomatoes, and orange juice (Table 6.1). Diets are more likely to be lower in potassium than sodium because we generally do not add potassium to foods. Some diuretics used to treat high blood pressure can also deplete the body's potassium stores. Thus, people who take diuretics need to monitor their potassium intake carefully. For them, high-potassium foods are necessary additions to the diet, as are potassium chloride supplements if prescribed by a physician. The bioavailability of potassium from these foods is high and is not influenced by other factors.

The potassium cation (K^+) is an important electrolyte, working with sodium and chloride to maintain proper fluid balance in the body. In addition, potassium is critical for muscle function, especially in heart tissue, nerve function, and energy metabolism. Whereas sodium causes a rise in blood pressure, consuming high amounts of potassium can decrease blood pressure in some people. Research showed that individuals consuming vegetarian diets, which are high in potassium, generally have lower blood pressure than non-vegetarians (Craig and Mengels 2009). Population surveys like the National Health and Nutrition Examination Survey (NHANES) also revealed that a diet low in potassium as well as calcium and magnesium is associated with hypertension (Townsend *et al.* 2005). A more recent study by Hedayati *et al.* (2012) further suggests that the effect of low potassium on high blood pressure is more pronounced among African Americans and may be even stronger than the effect of high sodium. In this study, the researchers analyzed data on over 3000 subjects, half of whom were African American, and found that the amount of potassium in urine samples is strongly correlated with blood pressure. There has been a lot of publicity about lowering salt or sodium in the diet in order to lower blood pressure. Based on recent literature, however, it appears that potassium plays at least an equally important role in contributing to hypertension as well.

As with sodium and chloride, regulation of blood potassium level is achieved mostly by the kidneys. In other words, when blood potassium is elevated, the kidneys excrete more potassium. The opposite is true when blood potassium is low. The hormone aldosterone, which is released by the adrenal glands and works on the kidneys, causes blood levels of sodium and chloride to increase while simultaneously causing blood levels of potassium to decrease.

The adequate intake of potassium for adults is 4700 mg per day. The daily value used to express potassium content on food and supplement labels is 3500 mg. On average, North Americans consume 2000 to 3000 mg per day. Thus, many of us need to increase our potassium intake, preferably by increasing fruit and vegetable consumption. Fruits, vegetables, fat-free or low-fat dairy foods and fish are good natural sources of potassium. Potassium-rich foods include sweet potatoes, greens, spinach, mushrooms, beans, peas, bananas, tomatoes, and oranges and orange juice.

Potassium deficiency is rarely seen owing to the abundance of the mineral in the diet, although it may result from diarrhea and vomiting. Heavy use of certain diuretics may also result in excessive potassium loss in the urine. Diuretics are drugs used to lower blood pressure by helping the body eliminate water. This reduces blood volume and helps decrease blood pressure. However, when the body excretes excessive amounts of water it also loses electrolytes. This can lead to low blood potassium, a condition called **hypokalemia**. People with eating disorders involving vomiting, such as bulimia nervosa, are at increased risk for hypokalemia. Potassium deficiency causes muscle weakness, irritability, and confusion. Recent studies also suggest that it may cause insulin resistance (Stumvoll *et al.* 2005). In severe cases, potassium deficiency may cause irregular heartbeats, muscle paralysis, decreased blood pressure, and difficulty breathing.

Calcium

Calcium is the most abundant mineral in the body. It represents 40 percent of all the minerals present in the body and equals about 1.2 kilograms (2.5 pounds). Calcium accounts for 1 to 2 percent of adult body weight. All cells need calcium, but more than 99 percent of the calcium in the body is used to strengthen bones and teeth. The remaining 1 percent is present in intracellular fluid, blood, and other extracellular compartments, where it plays vital roles in nerve transmission, muscle contraction, blood pressure regulation, and the release of hormones.

Dairy products, such as milk and cheese, provide about 75 percent of the calcium in our diets. Cottage cheese is an exception because most calcium is lost during production. Bread, rolls, crackers, and other foods made with milk products are secondary contributors. Other calcium sources are leafy greens such as spinach, broccoli, sardines, and canned salmon (Table 6.1). It is important to note that much of the calcium in some leafy green vegetables, notably spinach, is not absorbed owing to the presence of oxalate. Oxalate will bind with calcium, thereby impeding its absorption. Fat-free milk is the most nutrient-dense source of calcium because of its high bioavailability and low caloric content. Other common sources of calcium in our diets include calcium-fortified orange juice and other beverages such as soy milk, as well as calcium-fortified cottage cheese, breakfast cereals, breakfast bars, snacks, and chewable candies.

Calcium is absorbed by both active transport and passive diffusion. Active transport, a process that requires energy, depends on the active form of vitamin D and accounts for most absorption when intakes are low to moderate. When vitamin D is deficient, absorption decreases dramatically. At high intakes, passive transport becomes more important. Unlike sodium and chloride, and potassium, the amount of calcium in the body depends greatly on its absorption from the diet. Calcium requires an acidic environment in the gastrointestinal tract to be absorbed efficiently. Absorption of calcium is also affected by several other dietary factors, including the presence of lactose, which enhances calcium absorption, and tannins, fibers, phytates, and oxalates, which decreases calcium absorption. For example, as mentioned earlier, spinach is a high-calcium vegetable but only about 5 percent of calcium is absorbed; the rest is bound by oxalates and excreted in the feces. Other factors that enhance calcium absorption include blood levels of parathyroid hormone and the gradual flow of digestive contents through the intestine.

Calcium is important in the maintenance of bones and teeth, where it is primarily found with phosphorous as solid mineral crystals. The growth, maintenance, and repair of bone involves a complex relationship between the synthesis of new bone by bone-building cells, **osteoblasts**, and the breakdown of bone by **osteoclasts**. The degradation and resynthesize of bone is termed **bone remodeling** (Figure 6.1). Osteoclasts break down or degrade small amounts of bone, and in doing so minerals embedded in the bone matrix including calcium and phosphorous (discussed below) are released into the blood. Osteoblasts, on the other hand, take up free calcium and phosphorous and, along with collagen, form complex mixtures called **hydroxyapatites**, solid mineral crystals that add strength, rigidity, and flexibility to the bone. Calcium also plays important roles in cell communication and the regulation of various biological processes. Calcium helps regulate enzymes and is necessary in blood clotting. It is involved in transmitting chemical and electrical signals in nerves and muscles. It is necessary for the release of neurotransmitters, which allow nerve impulses to pass from one nerve to another and from nerves to other tissues. Inside the muscle cells, calcium allows the two contractile proteins, actin and myosin, to interact to cause muscle contraction. Calcium is also involved in blood pressure regulation by modulating the contraction of smooth muscle in the blood-vessel walls.

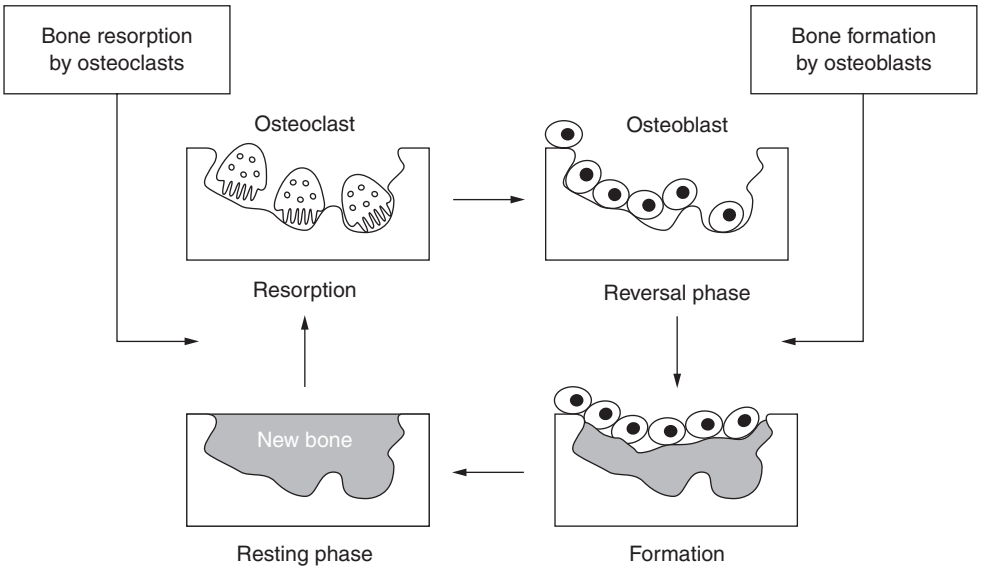

Figure 6.1 Normal cycle of bone remodeling

There is insufficient data available to generate RDA for calcium. The adequate intake (AI) for calcium for adults aged 19 to 50 is set at 1000 mg per day, which is based on the amount of calcium needed each day to offset calcium losses in urine, feces, and other routes. Since absorption decreases with age, the AI for men and women age 51 and older is increased to 1200 mg per day. For adolescents, the AI is higher than for adults; that is, 1300 mg per day for boys and girls aged 9 to 18. This higher number will support bone growth. The AI for calcium during pregnancy is not increased above non-pregnant levels. This is because there will be an increase in maternal calcium absorption during pregnancy which helps supply the calcium needed for the fetal skeleton.

In children, calcium deficiency results in rickets, a disease that may also be caused by vitamin D deficiency. As mentioned in Chapter 3, children with rickets have poor bone mineralization and characteristically "bowed" bones, especially in legs. Most bone is formed early in life. In children, bone formation occurs more rapidly than breakdown. Even after growth stops, bone mass continues to increase into young adulthood when peak bone mass is achieved. In adults, calcium deficiency may cause **osteopenia**, the moderate loss of bone mass. In older adults, calcium deficiency may cause osteoporosis, a more serious chronic disease that can lead to an increase in risk of bone fracture. A low calcium intake is the most significant dietary factor contributing to osteoporosis, but intake alone does not predict the risk of osteoporosis. Genetics as well as other dietary and lifestyle factors also affect calcium status and bone mass. As mentioned earlier, diets high in phytates, oxalate, and tannins reduce calcium absorption, as does low vitamin D status. Adequate protein is necessary for bone health but increasing protein intake increases urinary calcium losses. Despite this, high protein intakes are generally associated with a lower risk of osteoporosis. This is because diets higher in protein are typically higher in calcium, and bone mass depends more on the ratio of calcium to protein than the amounts of protein alone.

A deficient intake of calcium has also been linked to weight gain. Both cross-sectional and intervention studies have revealed an inverse relationship between calcium intake

and body fat mass, body weight, and the relative risk of obesity (Jacqmain *et al.* 1991, McCarron *et al.* 1984, Zemel *et al.* 2000). A number of different mechanisms have been suggested as being responsible for the effect of a high-calcium intake on energy balance. One possible explanation is reduced absorption of fat in the gut; another that intracellular calcium plays a regulatory role in fat metabolism. It has been hypothesized that high-calcium diets protect against fat gain by creating a balance of fat breakdown over fat synthesis in adipocytes (Zemel *et al.* 2000). Calcium homeostasis is maintained through the concerted actions of parathyroid hormone (PTH), calcitonin, and the vitamin D metabolites. When blood calcium levels fall below normal, responses of these regulatory factors can stimulate increases in intracellular concentrations of calcium, thereby reducing fat breakdown and enhancing fat synthesis in adipocytes (Zemel *et al.* 2000).

Calcium deficiency also affects other tissues. Because of calcium's role in muscle contraction and nerve function, low blood calcium can cause muscle pain, muscle cramps, and tingling in the hands and feet. More serious calcium deficiency causes muscles to tighten and become unable to relax, a condition called **tetany**.

Phosphorus

Phosphorus makes up about 1 percent of the adult body by weight, and 85 percent of this is found as a structural component of bones. Phosphorus is also a component of enzymes, genetic material such as DNA, and cell membranes. In nature, phosphorus is most often found in combination with oxygen as phosphate. Although no disease is currently associated with an inadequate phosphorus intake, a deficiency may contribute to bone loss in older women. The body can efficiently absorb phosphorus at about 70 percent of dietary intake. This high absorption rate, plus the wide availability of phosphorus in foods, makes this mineral less important than calcium in dietary planning. The active form of vitamin D enhances phosphorus absorption, as it does for calcium.

Like calcium, phosphorus is found in dairy products such as milk, yogurt, and cheese, but meat and bread are also common sources of phosphorus in the adult diet (Table 6.1). Breakfast cereals, bran, eggs, nuts, and fish are also good sources. About 25 percent of dietary phosphorus comes from food additives, especially in baked goods, cheeses, processed meats, and many soft drinks. In a 12-oz (1/3 liter) serving of a soft drink, there is about 50 to 75 mg of phosphorus existing in the form of phosphoric acid. Reliance on soft drinks to supply dietary phosphorus is not recommended, because they typically do not contain any other essential nutrients. In other words, they have low nutrient densities.

Cell membranes are made from phospholipids, which consist of phosphorus-containing polar head groups. Therefore, a primary role of phosphorus in the body is its function as a component of cell membranes. Phosphorus, along with calcium, is also required to form hydroxyapatite that contains a ratio of calcium to phosphate of 2:1. This crystal compound is believed to contribute to the rigidity of bones. Phosphorus is a component of a high-energy compound adenosine triphosphate (ATP) as well as our genetic materials such as DNA and RNA. In addition, phosphorus-containing compounds help maintain blood pH by acting as buffers that accept and donate hydrogen ions. Phosphorus is also involved in hundreds of metabolic reactions in the body. In these reactions, phosphate groups are transferred from one molecule to another, producing "phosphorylated" molecules. In fact, some molecules remain inactive until they are phosphorylated. For example, the enzyme needed to break down glycogen into its glucose subunits must be phosphorylated before it can work.

The RDA for phosphorus is set at 700 mg for adults 19 to 50 years of age. Because neither absorption nor urinary losses change significantly with age, the RDA is the same

for older adults. For growing children and adolescents, the RDA is based on the phosphorus intake necessary to meet the needs for bone and soft tissue growth. There is no evidence that phosphorus requirements are increased during pregnancy. This is because during the period of pregnancy, intestinal absorption increases by 10 percent, which is sufficient to provide the additional phosphorus needed by the mother and fetus.

Phosphorus deficiency results in loss of appetite, anemia, muscle weakness, poor bone development, and, in extreme cases, death. However, because phosphorus is so widely distributed in food, dietary deficiency of this particular mineral is rare. Marginal phosphorus deficiencies may be found in preterm infants, vegans, people with alcoholism, older people on nutrient-poor diets, and people with long-term bouts of diarrhea.

Magnesium

There are approximately 25 grams of magnesium in the adult human body. Over half of the body's magnesium is in the bones. Most of the rest is in the muscle and soft tissues, with only 1 percent in the extracellular fluid. Magnesium is important for nerve and heart function, and aids many enzyme reactions. Over 300 enzymes use magnesium, and many energy-yielding compounds in cells require magnesium to function properly.

Rich sources for magnesium are plant products, such as wholegrains like wheat bran, broccoli, potatoes, squash, beans, nuts, and seeds (Table 6.1). Magnesium is also found in leafy greens such as spinach and kale. Animal products, such as milk, fish, and meats, supply some magnesium. Two other sources of magnesium are hard tap water, which contains a high mineral content, and coffee. We normally absorb about 40 and 60 percent of the magnesium in our diets, but absorption efficiency can increase up to about 80 percent if intakes are low. The active form of vitamin D can enhance magnesium absorption, whereas the presence of phytate does the opposite. As calcium in the diet increases, the absorption of magnesium decreases, so the use of calcium supplements can reduce the absorption of magnesium.

The majority of magnesium in the body is associated with bone where it is essential for the maintenance of structure. Magnesium is a co-factor for over 300 enzymes. It is necessary for the production of energy from carbohydrates, lipids, and proteins. In these reactions, magnesium functions as either a stabilizer of ATP or an enzyme activator. Magnesium is also involved in regulating calcium homeostasis and is needed for the action of vitamin D and many hormones, including parathyroid hormone.

The adult RDA for magnesium is about 400 mg per day for men and about 310 mg per day for women. The daily value used to express magnesium content on food and supplement labels is 400 mg. Adult men consume an average of 320 mg daily, whereas women consume closer to 220 mg daily. This suggests that many of us should improve our consumption of magnesium-rich foods, such as wholegrain breads and cereals. If dietary means are not enough, a balanced multivitamin and mineral supplement containing approximately 100 mg of magnesium can help close the gap between intake and needs. As with most other supplements, the typical form used in supplements is not as well absorbed as the forms of magnesium found in foods, but still contributes to meeting magnesium needs.

Magnesium deficiency is rare in the general population, but is sometimes seen in those with alcoholism, malnutrition, kidney disease, and gastrointestinal disease, as well as those who use diuretics that increase magnesium loss via urine. Deficiency symptoms include nausea, muscle cramping, irritability, heart palpitations, and an increase in blood pressure. There is a great deal of interest in the possibility that mild magnesium deficiency may increase risk for cardiovascular disease (Alghamdi *et al.* 2005, Bobkowski *et al.* 2005, Weglicki *et al.* 2005). Some research also suggests that magnesium deficiency may predispose people to type 2 diabetes (Guerrero-Romero *et al.* 2005).

Sulfur

The body does not use sulfur on its own as a nutrient. Sulfur is mentioned here because it is a major mineral that occurs in essential nutrients such as the vitamins biotin and thiamin and the amino acids methionine and cysteine. Being part of the amino acids methionine and cysteine, sulfur is important for protein synthesis. Sulfur plays a role in determining the contours or structure of protein molecules. The sulfur-containing side chains in cysteine molecules can link to each other, forming disulfide bonds, which stabilize the protein structure. Sulfur also helps in the balance of acids and bases in the body.

There is no recommended intake for sulfur. Proteins supply the sulfur we need. As such, no deficiencies are known when protein needs are met (Table 6.1).

Trace minerals

As mentioned above, essential minerals are classified as major minerals or trace minerals, depending on how much we need. Major minerals are required in amounts greater than 100 mg/day, whereas less than 100 mg of each trace mineral is required daily. Information about trace minerals is one of the most rapidly expanding areas of knowledge in nutrition. With the exception of iron and iodine, the importance of trace minerals to humans has been recognized only within the past 50 years. Although we need 100 mg or less of each trace mineral daily, they are just as essential to good health as major minerals. Further details on some of the major trace minerals, including iron, zinc, selenium, iodine, chromium, copper, and fluoride, are provided as follows.

Iron

Of all the trace minerals, iron (Fe) is likely the most studied. Its role as a major constituent of blood was identified in the eighteenth century when iron tablets were available for treating young women in whom "coloring matter" was lacking in the blood. Today, we know that the red color in blood is due to the iron-containing protein called **hemoglobin** and that a deficiency of iron decreases hemoglobin production. Although the importance of dietary iron has long been recognized, iron deficiency is still one of the most common nutrition deficiencies worldwide today. Iron is found in every living cell, adding up to about 5 grams (1 teaspoon) for the entire body.

Iron in the diet comes from both plant and animal sources. Much of the iron in animal products is **heme iron** which is part of a chemical complex found in animal protein such as hemoglobin in blood and **myoglobin** in muscle. Meat, poultry, and fish are good sources of heme iron. Heme iron accounts for 10 to 15 percent of the dietary iron. Leafy green vegetables, legumes, and whole and enriched grains are good sources of **non-heme iron**, which may not be absorbed as well as heme iron. Most of the iron in bakery items has been added to refined flour in the enrichment process. Another source of non-heme iron in the diet is iron cooking utensils from which iron leaches into food. Leaching is enhanced by acidic foods. For example, spaghetti sauce cooked in a glass pan contains about 3 mg of iron, but the same sauce cooked in an iron skillet may contain as much as 50 mg. Milk is a poor source of iron. A common cause of iron-deficiency anemia in children is an overreliance on milk, coupled with an insufficient meat intake. Vegetarians who omit all animal products are particularly susceptible to iron-deficiency anemia because of their lack of dietary heme iron.

The bioavailability of iron is complex and influenced by many factors, including its form, a person's iron status, and the presence or absence of other dietary components.

For example, the bioavailability of heme iron is two to three times greater than of non-heme iron. Absorption of heme iron is high and most affected by iron status. However, many factors can influence absorption of non-heme iron. One of the most important factors affecting non-heme iron absorption is its ionic state. Non-heme iron is found in two ionic forms in foods: the more oxidized **ferric iron** (Fe^{3+}) and the more reduced **ferrous iron** (Fe^{2+}). The more reduced ferrous form is found to be more readily absorbed. One of the best-known enhancers of iron absorption is vitamin C, which converts ferric iron into ferrous iron in the intestinal lumen. Thus, consuming vitamin C in a meal that contains non-heme iron enhances the bioavailability of the iron. Stomach acid also helps reduce ferric iron to ferrous iron, and some studies suggest that the chronic use of antacids to neutralize stomach acidity can decrease non-heme iron absorption.

Dietary factors that interfere with the absorption of non-heme iron include fiber. Phytate found in cereals, tannins found in tea, and oxalates found in leafy greens such as spinach can prevent absorption by binding iron in the gastrointestinal tract. The presence of other minerals may also decrease iron absorption. For example, calcium supplements decrease iron absorption, particularly when both are consumed at the same meal.

Iron is part of the hemoglobin in red blood cells and myoglobin in muscle cells. Hemoglobin molecules transport oxygen from lungs to cells and assist in the return of some carbon dioxide from cells to the lungs for excretion. Without sufficient hemoglobin, oxygen availability to tissues decreases. This may result in lack of energy and fatigue. Myoglobin is another oxygen-carrying molecule. It acts as a reservoir of oxygen, releasing oxygen to muscle cells when needed for energy production. In addition to transporting and delivering oxygen to cells, iron is also needed for other aspects of energy metabolism. For example, it is a basic component of **cytochromes**, which are heme-containing protein complexes that function in the electron transport chain. Cytochromes serve as electron carriers, allowing for the conversion of adenosine diphosphate (ADP) to adenosine triphosphate (ATP). Among other functions of iron include helping to metabolize drugs and remove toxins from the body, and serving as a co-factor for antioxidant enzymes that stabilize free radicals and for enzymes needed for DNA synthesis.

The daily adult RDA for iron for men aged 19 to 50 and for women aged over 50 is 8 mg. For women aged 19 to 50 the RDA is 18 mg. The higher RDA for young and middle-aged women is primarily because of menstrual blood loss. Women who menstruate more heavily and longer than average may need even more dietary iron than those who have lighter and shorter flows. The daily value used to express iron content on food and supplement labels is 18 mg, but it increases to 27 mg for pregnant women. Most women do not consume 18 mg of iron daily. The average daily intake is closer to 13 mg, while in men it is about 18 mg per day. Therefore, women should seek out iron-fortified foods such as ready-to-eat breakfast cereals that contain at least 50 percent of the daily value. Use of a balanced multivitamin and mineral supplement containing up to 100 percent of daily value for iron is another option.

Iron deficiency is the most common nutritional deficiency in the United States and the world. Because iron requirements increase during growth and development, iron deficiency is typically seen in infants, growing children, and pregnant women. Iron is lost in the blood each month during the menstrual cycle. Therefore, women of childbearing age are also at increased risk for iron deficiency. Although iron deficiency was once thought to cause only anemia, scientists now know that it can influence many aspects of health. Mild iron deficiency is associated with fatigue and impaired physical work performance. In addition, it can cause behavioral abnormalities and impaired cognitive function in children (Black 2003, Bryan *et al.* 2004). Mild iron deficiency also impairs body temperature regulation, especially in cold conditions (Rosenzweig and

Volpe 1999) and may negatively influence the immune function (Cunningham-Rundles and McNeeley 2005, Failla 2003). Some studies also suggest that mild iron deficiency during pregnancy increases the risk of premature delivery, low birth weight, and maternal mortality (Gambling *et al.* 2003).

When iron is deficient, hemoglobin cannot be produced. When not enough hemoglobin is available, the red blood cells that are formed are fewer than normal and are unable to deliver adequate oxygen to the tissues. This is known as **iron deficiency anemia**. The signs and symptoms of anemia include weakness, headache, fatigue, rapid heart rate, shortness of breath, lack of concentration, and an inability to regulate body temperature, all of which may be ascribed to inadequate oxygen supply to cells. As estimated by the World Health Organization, as much as 30 percent of the world's population suffer from iron deficiency anemia. Women of reproductive age are at risk for iron deficiency anemia because of iron loss due to menstruation. Iron deficiency is common among pregnant women, despite the absence of menstruation. This is because the need for iron is increased due to the expansion of maternal blood volume and growth of the fetus. Iron deficiency is also common in children and adolescents. The rapid growth and increase in muscle mass and blood volume increase iron needs. Athletes are another group at risk for iron deficiency due to greater iron loss coupled with a low iron intake as a consequence of vigorous training. It is recommended that dietary intake of iron required by athletes should be at least 30 percent more than that of the general population (Institute of Medicine (US) Panel on Micronutrients 2001).

Zinc

The essentiality of zinc in the human diet was only recognized in the 1960s in Egypt and Iran, when a syndrome of growth retardation and poor sexual development, seen in Egyptian and Iranian men consuming a diet based on vegetable protein, was alleviated by supplemental zinc. Although the diet was not low in zinc, it was found that the absorption of zinc was reduced due to a lack of animal protein and almost exclusive use of unleavened bread. Unleavened bread is very high in phytate, which can interfere with zinc bioavailability. Zinc deficiencies were first observed in the United States in the early 1970s in hospitalized patients who were fed with an intravenous injection of certain amino acids. Such amino acid formulas are low in trace minerals compared to whole protein.

In general, protein-rich diets are also rich in zinc. Animal foods supply almost half of an individual's zinc intake. Major sources of zinc are beef, poultry, eggs, milk, seafood, bread, and fortified breakfast cereals. Animal foods are our primary sources of zinc because zinc from animal sources is not bound to phytate. Wholegrains are also a good source, but refined grains are not because zinc is lost in milling and not added back in enrichment. Grain products leavened with yeast provide more zinc than unleavened products because the yeast leavening of breads reduces the phytate content. Because zinc, iron, and calcium share the same transport proteins in the intestinal cells, high intake of iron and calcium can decrease zinc absorption.

Zinc is the most abundant intracellular trace mineral. It is found in the cytosol, organelles, and nucleus. Approximately 200 enzymes require zinc as a co-factor for activity. For example, zinc is involved in the functioning of superoxide dismutase, which is vital for protecting cells from free radical damage. It is also needed by enzymes that function in the synthesis of DNA and RNA, in carbohydrate metabolism, in acid–base balance, and in a reaction that is necessary for folate absorption. Zinc plays a role in the storage, release, and function of insulin, the mobilization of vitamin A from the liver, and the stabilization of the cell membrane. It influences the hormonal regulation of cell

division and is therefore needed for the growth and repair of tissues. In addition, zinc may reduce the risk for developing cancer by improving immune function while promoting apoptosis in cancer cells (Prasad *et al.* 2009). Although zinc supplements are often touted as helping to "cure" the common cold, most studies do not support this claim (Jackson *et al.* 2000).

The adult RDA for zinc is 11 mg for men and 8 mg for women. The values were based on the amount to cover daily losses of zinc. During pregnancy, the recommendation for zinc is increased on account of the zinc that accumulates in maternal and fetal tissues. The daily value used to express zinc content on food and supplement labels is 15 mg. There are no indications of moderate or severe zinc deficiencies in an otherwise healthy adult population. It is likely, however, that some people such as women, poor children, vegans, the elderly, and people with alcoholism can have a borderline zinc deficiency. People who show deterioration in taste sensation, recurring infections, poor growth, or slow wound healing should have their zinc status checked.

The symptoms of zinc deficiency include poor growth and sexual development, skin rashes, impaired immune function, and delayed sexual maturation. These symptoms reflect the fact that zinc is important in protein synthesis and gene expression. The risk of zinc deficiency is greater in areas of the world where the diet is high in phytate, fiber, tannins, and oxalates. Such a risk is also higher in the elderly, low-income children, and vegetarians. Supplements have been shown to reduce the incidence of diarrhea and infections in children in developing countries (Fraker *et al.* 2000).

Selenium

Although the discovery of selenium can be traced back more than 150 years, the essentiality of this trace mineral in human nutrition was not recognized until the 1960s. Since that time, much has been learned about how the body uses selenium for carrying out various vital functions. Selenium exists in many readily absorbed forms. Like zinc, selenium has an indirect antioxidant function. Selenium's best understood role is as part of an enzyme, such as glutathione peroxidase, that works to reduce damage to cell membranes from electron-seeking, free-radical compounds. Food contains several forms of selenium, but typically it is associated with the amino acid methionine. Usually methionine contains sulfur. However, selenium often substitutes for sulfur due to the similarity in chemical characteristics between sulfur and selenium. When methionine contains selenium, it is called selenomethionine.

The best animal sources of selenium are nuts, seafood, and meats. Fruits, vegetables, and drinking water are generally poor sources. Grains can be a good plant source, depending on the selenium content of the soil where they were grown. For example, in some areas of China where the soil selenium content is very low, grains contain negligible amounts. However, in some parts of the western United States where the soil selenium content is very high, grains may contain toxic levels. Soil selenium content can have a significant impact upon the selenium intake of populations consuming primarily locally grown food. However, as we normally eat a variety of foods supplied from many geographic areas, it is unlikely that low soil selenium in a few locations will mean inadequate selenium in our diets. Major selenium contributors to the adult diet are animal and grain products.

The bioavailability of selenium in foods is high, and absorption of this mineral in the intestine is not regulated. Therefore, almost all selenium that is consumed enters the blood. Once selenium is absorbed, homeostasis is maintained by regulating its excretion in the urine. As mentioned earlier, selenium is an essential part of the enzyme glutathione peroxidase. Glutathione peroxidase neutralizes peroxides so that they no longer

form free radicals which cause oxidative damage. By reducing free radical formation, selenium can spare some of the requirement for vitamin E, because vitamin E is used to stop the action of free radicals once they are produced (Figure 6.2). Recall in Chapter 5 that vitamin E helps prevent attacks on cell membranes by donating electrons to electron-seeking compounds. In this regard, it seems possible that selenium and vitamin E can work together toward the same goal. However, this claim remains to be seen, as a recent study has failed to show that the supplementation of selenium in conjunction with vitamin E would reduce the risk for prostate cancer (Klein *et al.* 2011). Selenium is also needed for synthesis of the thyroid hormones, which regulate the basal metabolic rate.

The RDA for selenium is 55 µg per day for adults. This intake maximizes the activity of selenium-dependent enzyme glutathione peroxidase in the blood. The daily value used to express selenium content on food and supplement labels is 70 µg. In general, adults meet the RDA, consuming on average 105 µg of selenium each day. Although selenium could prove to play a role in immune function and the prevention of cancer, at this point it seems premature to recommend selenium supplementation for this purpose.

Symptoms of selenium deficiency include muscle pain, discomfort, and weakness. A form of heart disease called Keshan disease may also occur with selenium deficiency. Keshan disease is a congestive cardiomyopathy caused by a combination of dietary deficiency of selenium and the presence of a mutated strain of Coxsackievirus, named after the Keshan County of Heilongjiang province, northeast China, where symptoms were first noted. The treatment for these disorders is selenium supplementation. It is considered that selenium supplements may relieve most of the symptoms of Keshan disease and reduce its incidence (Chen 2012).

Iodine

Iodine is needed for the synthesis of thyroid hormones which regulate growth, reproduction, and energy metabolism. In the early 1900s, iodine deficiency was common in the central United States and Canada, and a condition associated with deficiency of

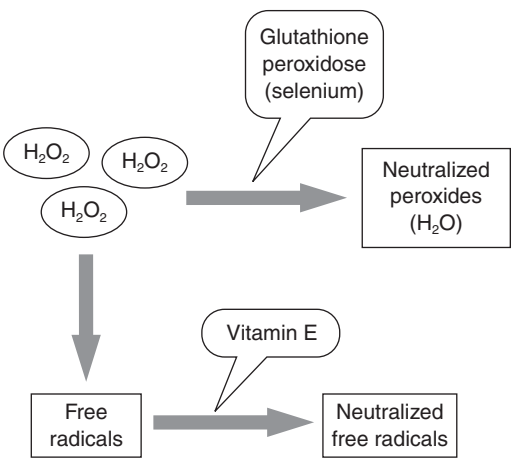

Figure 6.2 The action of the selenium-containing enzyme glutathione peroxidase. The enzyme neutralizes peroxides before they form free radicals, which will then spare some of the need for vitamin E

iodine is known as **goiter**, an enlarged thyroid gland. The soils in these areas have low iodine content. In the 1920s, researchers in Ohio found that low doses of iodine given to children over a four-year period could prevent goiter. This finding led to the addition of iodine to salt beginning in the 1920s. Today, many nations such as Canada require iodine fortification of salt. In the United States, salt may be purchased either iodized or plain. Iodine deficiency still remains a world health problem. About 2 billion people worldwide are at risk of iodine deficiency, and approximately 800 million of these people have suffered the various effects of the deficiency.

Saltwater fish, seafood, and iodized salt contain various forms of iodine. Dairy products may contain iodine because of the iodine-containing additives used in cattle feed and the use of iodine containing disinfectants on cows, milking machines, and storage tanks. Sea salt found in health food stores, however, is generally not a good source because the iodine is lost during processing.

Iodine is highly bioavailable, being almost completely absorbed in the small intestine and, to a lesser extent, the stomach. Once in the blood, iodine is rapidly taken up by the thyroid gland and used for the production of thyroid hormones. Thyroid hormones are synthesized using iodine and the amino acid tyrosine. If a person's iodine intake is insufficient, the thyroid gland enlarges as it attempts to take up more iodine from the bloodstream. This eventually leads to the development of goiter. Simple goiter is a painless condition, but if uncorrected it can lead to pressure on the trachea, which may cause difficulty in breathing. Although iodine can prevent goiter formation, it does not significantly shrink a goiter once it has formed. Surgical removal may be required in severe cases.

The RDA for iodine for adults is 150 µg to support thyroid gland function. This is the same as the daily value used to express iodine content on food and supplement labels. A half-teaspoon of iodine-fortified salt supplies that amount. Most adults consume more iodine than the RDA. The iodine in our diets adds up because dairies and fast-food restaurants use it as a sterilizing agent, bakeries use it as a dough conditioner, food producers use it as part of food colorants, and it is added to salt. There is concern, however, that vegans may not consume enough unless iodized salt is used.

Iodine deficiency reduces the production of thyroid hormones. As a result, metabolic rate slows down, causing fatigue and weight gain. As mentioned earlier, the most obvious sign of deficiency is goiter, an enlarged thyroid gland. If iodine is deficient during pregnancy, it increases the risk of stillbirth or fetal death and spontaneous abortion. Deficiency also can cause a condition called **cretinism** in offspring. Cretinism is characterized by symptoms such as mental retardation, deaf mutism, and growth failure. Iodine deficiency during childhood and adolescence may also result in goiter and impaired mental function.

Chromium

The importance of chromium in human diets has been recognized only in the past 40 years. The most-studied function of chromium is the maintenance of glucose uptake into cells. Our current understanding is that chromium enters the cell and acts to enhance the transport of glucose and amino acids across the cell membrane by aiding insulin function. On the market of sports supplements, chromium is recognized by many as the popular supplement chromium picolinate, which is promoted to increase lean body mass, although this claim has yet to be validated.

Specific data regarding the chromium content of various foods are limited, and most food composition tables do not include values for this trace mineral. Egg yolks, wholegrains, organ meats, mushrooms, nuts, and beer are good sources. Milk, vegetables, fruits as well as refined carbohydrates such as white breads, pasta, and white rice are

poor sources. The amount of chromium in foods is closely tied to the local soil content of chromium. To provide yourself with a good chromium intake, regularly choose wholegrains in place of mostly refined grains.

Chromium is needed for the hormone insulin to function properly in the body and appears to be especially important in regulating its function in people with type 2 diabetes. When carbohydrates are consumed, insulin is released and binds to receptors in cell membranes. This binding triggers the uptake of glucose by cells and an increase in protein and lipid synthesis. Chromium is part of a small peptide that stabilizes the bound insulin, thereby augmenting insulin action. With chromium deficient, it takes more insulin to produce the same effect. Chromium is also required for normal growth and development in children. In addition, it increases lean mass and decreases fat mass – at least in laboratory animals (McNamara and Valdez 2005, Page *et al.* 1993). Because of this, chromium in a form called chromium picolinate has been widely marketed as an ergogenic aid for athletes (Lukaski 1999). However, the most controlled studies investigating the effect of this supplement on athletic performance and blood glucose regulation have shown no beneficial outcomes (Pittler *et al.* 2003, Vincent 2003).

The adequate intake (AI) for chromium is 35 µg per day for men and 25 µg per day for women based on the amount present in a balanced diet. The AI is increased during pregnancy and lactation. The AI for older adults is slightly lower because energy intake decreases with age. Average adult intakes are estimated at 30 µg per day, but could be somewhat higher.

Symptoms of chromium deficiency include impaired blood glucose tolerance with diabetes-like symptoms such as elevated blood glucose levels and increased insulin levels. Chromium deficiency may also cause elevated blood cholesterol and triglyceride levels. The mechanism by which chromium influences cholesterol metabolism is not known but may involve enzymes that control cholesterol synthesis.

Copper

Copper is present in two forms: its oxidized **cupric** (Cu^{2+}) and its reduced **cuprous** form (Cu^{+}). Note that, as with iron, the ending "-ous" represents the more reduced form, whereas the ending "-ic" represents the more oxidized form. Copper is a co-factor for several enzymes involved in a wide variety of processes such as ATP production and protection from free radicals. Cupper and iron share many similarities in terms of food sources, absorption, and functions in the body.

Copper is found primarily in liver, seafood, cocoa, legumes, nuts, seeds, and wholegrain breads and cereals. As with many other trace elements, soil content affects the amount of copper in plant foods.

About 30 to 40 percent of the copper in a typical diet is absorbed. The absorption of copper is affected by the presence of other minerals and vitamins in the diet. The zinc content of the diet can have a major impact upon copper absorption. There is antagonism in absorption between zinc and copper. When zinc intake is high, it simulates the synthesis of protein metallothionein in mucosal cells. Metallothionein preferentially binds copper rather than zinc, thereby preventing copper from being moved out of mucosal cells into the blood. Copper absorption is also reduced by high intakes of iron and manganese. Other factors affecting copper absorption include vitamin C and large doses of antacid, which inhibit copper absorption and, over the long term, may cause copper deficiency.

Once absorbed, copper binds to albumin, a protein in the blood, and travels to the liver, where it binds to the protein ceruloplasmin for delivery to other tissues. Copper can be removed from the body and subsequently eliminated in the feces.

Copper is a co-factor for many enzymes involved in reduction–oxidation reactions important in ATP production, iron metabolism, neural function, antioxidant function, and connective tissue synthesis. For example, copper serves as a co-factor for the enzyme cytochrome c oxidase, which combines electrons, hydrogen ions, and oxygen to form water in the electron transport chain. Copper is also a co-factor for the enzyme superoxide dismutase, which converts the superoxide free radical (O_2^-) into the less harmful hydrogen peroxide molecule (H_2O_2). The synthesis of norepinephrine, a neurotransmitter, and collagen needed for connective tissue also requires copper.

The RDA for copper is 900 µg daily for adults, based on the amount needed for activity of copper-containing proteins and enzymes in the body. The average adult intake is about 1 to 1.6 mg per day. The form of copper typically found in multivitamin and mineral supplements is not readily absorbed. It is best to rely on food sources to meet copper needs. The copper status of adults appears to be good, though we lack sensitive measures to determine copper status.

Severe copper deficiency is relatively rare, occurring most often in preterm infants. The most common manifestation of copper deficiency is anemia. This is due primarily to the fact that the copper-containing protein ceruloplasmin is needed for iron transport. In copper deficiency, even if iron is sufficient in the diet, iron cannot be transported out of the intestinal mucosa. Copper deficiency causes skeletal muscle abnormality similar to those seen in vitamin C deficiency. This is because the enzyme needed for the cross-lining of connective tissue requires copper in addition to vitamin C. Because of copper's role in the development and maintenance of the immune system, a diet low in copper can decrease the immune response and thus increase the incidence of infection.

Fluoride

Fluoride has its greatest effect on dental caries prevention early in life. This link was found as dentists in the early 1900s noticed a lower rate of dental caries in the southwestern United States. These areas contain high amounts of fluoride in the water. After experiments showed that fluoride in the water did indeed decrease the rate of dental caries, controlled fluoridation of water in parts of the United States began in 1945. It has been evidenced that those who grew up drinking fluoridated water generally have 40 to 60 percent fewer dental caries than people who did not drink fluoridated water as children.

Tea, seafood, seaweed, and some natural water sources are the only good food sources of fluoride. Most of our fluoride intake comes from fluoride added to drinking water and toothpaste, and from fluoride treatments performed by dentists. Fluoride is not added to bottled water. Therefore, if people such as children consume bottled water, they won't receive fluoride from such water intake. Cooking utensils also affect food fluoride content. Foods cooked with Teflon utensils can pick up fluoride from the Teflon, whereas aluminum cookware can decrease fluoride content.

The gastrointestinal tract provides very little fluoride regulation. In fact, almost all fluoride consumed is absorbed in the small intestine and then circulates in the blood to the liver and then to the bones and teeth. Fluoride has a high affinity for calcium. In teeth, fluoride is incorporated into the enamel crystals, where it forms the compound fluorhydroxyalatite, which is more resistant to acid than the hydroxyalatite crystal it replaces. As a result, fewer cavities are formed. Fluoride also appears to stimulate maturation of osteoblasts, the cells that build new bone, and has therefore been suggested to strengthen bones in adults with osteoporosis.

The adequate intake for fluoride for adults is 3.1 to 3.8 mg per day. This range of intake provides the benefits of resistance to dental caries without causing ill-effects. Typical fluoridated water contains about 1 mg per liter, which works out to about 0.25 mg per cup.

No deficiency symptoms are known. However, fluoride toxicity is well documented. Signs and symptoms include gastrointestinal upset, excessive production of saliva, watering eyes, heart problems, and, in severe cases, coma. In addition, very high fluoride intake causes pitting and mottling of teeth, often referred to as dental **fluorosis**, and a weakening of the skeleton called skeletal fluorosis.

Water

Water (H_2O), the most abundant molecule in the human body, is truly the essence of life. The body needs more water each day than any other nutrient. An average individual can survive only a few days without water, whereas a deficiency of other nutrients may take weeks, months, or even years to develop. Water is found both inside and outside of cells, and although some water is made in the body during metabolism, it is an essential nutrient. Acting as a solvent, it dissolves many body compounds such as sodium chloride (table salt). Water is the perfect medium for body processes because it enables chemical reactions to occur. Water even participates directly in many of these reactions, such as hydrolysis. Water also helps regulate body temperature. Water balance within different compartments of the body is vital for health and is regulated by the movement of electrolytes such as sodium and potassium.

Fluid balance and electrolytes

Water forms the greatest component of the human body, making up 50 to 70 percent of the body's weight (about 40 liters, or 10 gallons). Water is found in varying proportions in all tissues of the body. Blood is about 90 percent water, muscle about 75 percent, bone about 25 percent, and adipose tissue about 20 percent water. About two-thirds of body water is found inside cells known as **intracellular fluid** (Figure 6.3). The remaining one-third is located outside cells as **extracellular fluid**. Extracellular fluid includes primarily blood plasma, lymph, and the fluid between cells called **interstitial fluid**. The concentration of substances dissolved in body water, or solutes, varies among these body compartments. For example, the concentration of protein is highest in intracellular fluid, lower in extracellular fluid, and even lower in interstitial fluid. Extracellular fluid has a higher concentration of sodium and chloride and a lower concentration of potassium, and intracellular fluid is higher in potassium and lower in sodium and chloride.

Although water can travel freely into and out of cells across the cell membrane, the body controls the amount of water in the intracellular and extracellular compartments mainly by monitoring ion concentrations. **Ions** are minerals that dissolve in water and are either positively or negatively charged. These charged ions allow the transfer of electric current; therefore they are called **electrolytes**. While sodium (Na^+) and chloride (Cl^-) are primarily found in the extracellular fluid, potassium (K^+) and phosphates (PO^{-4}) are in the intracellular fluid.

The concentration of these electrolytes must be maintained within certain ranges for cells to function properly. Cell membranes control the movement of most substances into and out of cells. For example, sodium and chloride cannot cross cell membranes passively but instead need help from membrane-bound transport proteins or "pumps" and the input of energy (ATP). Thus, the movement of electrolytes into and out of cells is an active transport process. However, water is unique in that it passes freely across cell membranes, making this a passive transport process. The body can couple the active pumping of ions across cell membranes with the passive movement of water. In doing so, fluid movement and balance are maintained in the various compartments at appropriate levels.

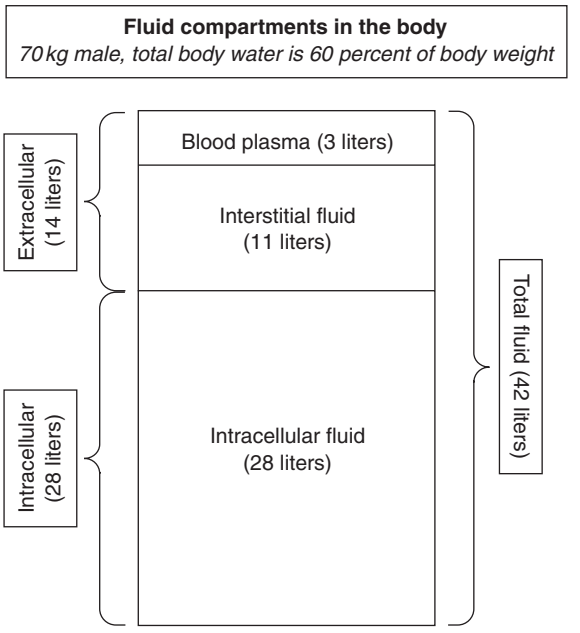

Figure 6.3 Fluid compartments and their relative proportions to the total fluid volume for an average individual

Movement of water across membranes via osmosis

Just as the body maintains the concentrations of other substances such as glucose within specific ranges, it also tightly regulates the amounts of water within the various fluid compartments. The movement of water from one compartment to another depends on fluid pressure and on the concentration of solutes in each compartment. The fluid pressure of blood against blood-vessel walls, or blood pressure, causes water to move from the blood into interstitial space. The difference in the concentration of solutes between capillaries and interstitial space causes much of this water to re-enter the capillaries. When the concentration of solutes in one compartment is higher than in another, water will move to equalize the solute concentration. This diffusion of water across a membrane from an area with a lower solute concentration to an area with a higher solute concentration is called **osmosis**. Osmosis occurs when there is a selectively permeable membrane, such as a cell membrane, which allows water to pass freely but regulates the passage of other substances (Figure 6.4). For example, when sugar is sprinkled on fresh strawberries, the water inside the strawberries moves across the skin of the fruit to try to equalize the sugar concentration on each side, causing the fruits to shrink.

Under normal conditions, concentrations of electrolytes on both sides of the cell membrane are similar or **isotonic**. Thus, water movement into and out of the cell is in equilibrium (Figure 6.5). However, if the intracellular concentration of electrolytes is greater than the extracellular concentration (thus intracellular is considered **hypertonic**), water will flow freely into the cell. If too much water flows in, the cell may burst. The opposite may also occur. When the intracellular concentration of electrolytes is relatively lower than the extracellular environments (thus intracellular is considered **hypotonic**), water will exit the cell, leading to cell shrinkage.

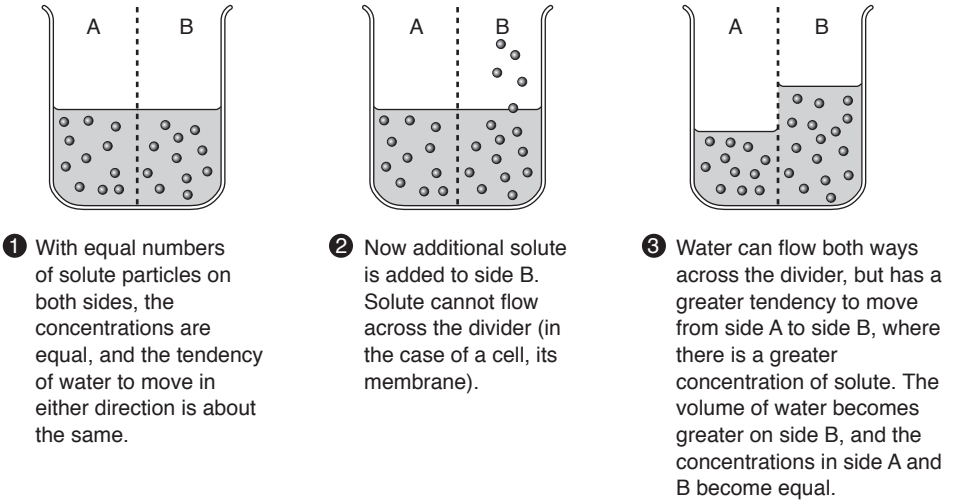

Figure 6.4 Water flows in the direction of the more highly concentrated solutions due to osmosis

Source: Whitney and Rolfes (2005). Used with permission.

The body can regulate the amount of water in each compartment by adjusting the concentration of solutes and relying on osmosis to move water. One such example will be the active transport of sodium into the cells that line the colon, causing water to be absorbed as well. Without this absorption, excessive amounts of water would be lost in the feces. An example of how osmosis may have negative health consequences is the regulation of blood volume and blood pressure. Recall that high salt (sodium chloride) intake can lead to increased blood volume and blood pressure in some people. This is because salt-sensitive people are unable to excrete excess sodium, resulting in high levels of sodium in the blood. This in turn causes water to move into the intravascular space, increasing blood volume and thus blood pressure.

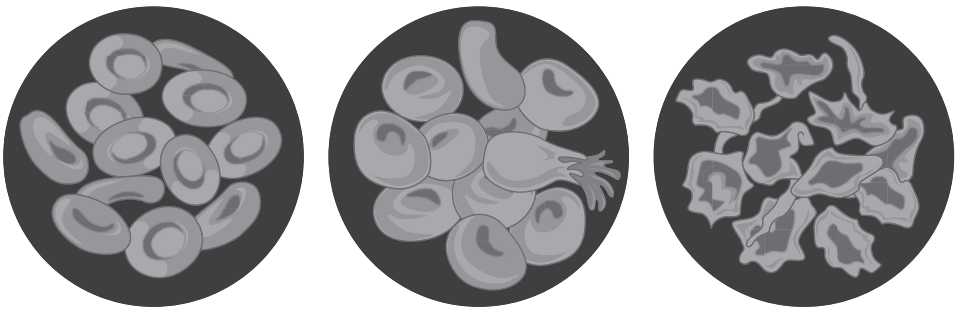

Figure 6.5 Effect of osmosis on cells

Function of water

Water plays an active role in many processes, including hundreds of chemical reactions. Water also helps keep the body at a constant temperature, even when the environment is very cold or very hot. In addition, water provides protection, helps remove waste products, and serves as an important solvent and lubricant.

Water as a solvent, transport medium, and lubricant

Water is an ideal solvent for some substances because it is polar; that is, the two poles of water molecules have different electrical charges. The polar nature of water allows it to surround other charged molecules and disperse them. Table salt consists of a positively charged sodium ion bound to a negatively charged chloride ion. When placed in water, the sodium and chloride ions move apart or dissociate because the positively charged sodium ion is attracted to the negative pole of the water molecule and the negatively charged chloride ion is attracted to the positive pole. Because of this polar nature, water is the primary solvent in blood, saliva, and gastrointestinal secretions. For example, blood is a solution consisting of water and a variety of dissolved solutes, including nutrients and metabolic waste products such as carbon dioxide and urea. Substances dissolved in blood can move from inside the blood-vessel out into the watery environment within and around tissues and cells, delivering important nutrients and allowing for the removal of waste products.

Water is also a lubricant. This is especially true in the gastrointestinal tract, respiratory tract, skin, and reproductive system, which produce important secretions such as digestive juices, mucus, sweat, and reproductive fluids, respectively. The ability of the body to incorporate water into these secretions is vital for health. For example, water is needed for producing functional mucus in the lungs. Mucus both protects the lungs from environmental toxins and pathogens, and lubricates lung tissue so that it will remain moist and supple. Water also helps form the lubricants found in knees and other joints of the body. It is the basis for saliva, bile, and amniotic fluid. Amniotic fluid acts as a shock absorber surrounding the growing fetus in the mother's womb.

Water regulates body temperature

When energy-yielding nutrients such as amino acids, glucose, and fatty acids are metabolized, energy is released. Some of this energy becomes heat and helps maintain the internal body temperature at a comfortable 98.6°F. However, excess heat generated by metabolism must be removed from the body so that the body's temperature does not rise. Hot environments can also raise the body's internal temperature.

The fact that water changes temperature slowly in response to changes in the external environment helps the human body resist temperature change when the outside temperature fluctuates. The term **specific heat** refers to the amount of energy it takes to increase the temperature of 1 gram of a substance by 1°C. Water has a high specific heat, meaning that changing its temperature takes a high amount of energy. Because water can handle so much energy without heating up, our body can maintain a relatively stable internal temperature even when metabolic rates are high or the environment is hot. The water in blood actively regulates body temperature. When body temperature starts to rise, the blood-vessels in the skin dilate, causing blood to flow close to the surface of the body and release some of the heat into the environment. This occurs with fevers as well as when the environmental temperature rises. The most

obvious way that water helps regulate body temperature is through the evaporation of sweat. When the body temperature increases, the sweat glands in the skin increase their secretions. As the sweat evaporates from the skin, heat is lost. Each liter of perspiration evaporated represents approximately 600 kcal of energy lost from the skin and surrounding tissues. Similarly, the heat lost when we have a fever increases one's need for calories. The role water plays in regulating body temperature is further discussed in Chapter 16.

Water helps remove waste products

Water is an important vehicle for transporting substances throughout the body and for removing waste products from the body. Most unusable substances in the body can dissolve in water and exit the body through urine. Urea is a major waste product. This byproduct of protein metabolism contains nitrogen. The more protein we eat in excess of needs, the more nitrogen we remove from amino acids and excrete in the form of urea in the urine. Likewise, the more sodium we consume, the more sodium we excrete in the urine. Overall, the amount of urine a person needs to produce is determined primarily by excess protein and salt intake.

A typical volume of urine produced per day is about 1 liter or more, depending largely on the intake of fluid, protein, and sodium. A somewhat greater urine output than that is fine, but less, especially less than 500 milliliters (~2 cups), forces the kidneys to form concentrated urine. The easy way to determine if water intake is adequate is to observe the color of one's urine. Whereas urine should be clear or pale yellow, concentrated urine is very dark yellow.

Estimating water needs

The recommended total intake of water per day is 2.7 liters (11 cups) for adult women and 3.7 liters (15 cups) for adult men. This is based primarily on our typical total water intakes from a combination of fluids and foods. For fluid alone this corresponds to about 2.2 liters (9 cups) for women and about 3 liters (13 cups) for men. Water needs can also be calculated based on energy requirement; that is, the greater the energy requirement, the greater the water needs. Adults need about 1 ml of water per kilocalorie of energy requirement, or about 2 to 3 liters per day.

We consume water in various liquids, such as fruit juice, coffee, tea, soft drinks, and water. Coffee, tea, and soft drinks often contain caffeine, which increases urine output. However, the fluid consumed from these beverages is not completely lost in urine, so these fluids still help to meet water needs. Foods also supply water, and many fruits and vegetables comprise more than 80 percent water (Table 6.2).

This amount is sufficient under average conditions, but water needs can be increased by variations in activity, environment, and diet. For example, a person exercising in a hot environment may require an additional 1–2 liters or more per day to replace water losses through sweating. Water needs can also be affected by the composition and adequacy of the diet. A low-energy coupled with high-protein diet increases water needs because water losses increase due to the need to excrete waste such as ketone and/or ammonia. A high-sodium diet increases water needs because the excess salt must be excreted in the urine. A high-fiber diet also increases water needs because more fluid is retained in the gastrointestinal tract.

Table 6.2 Water content of various foods

Fruits	*Water (%)*	*Vegetables*	*Water (%)*	*Others*	*Water (%)*
Apple	84	Broccoli	91	Beer	90
Apricot	86	Cabbage (green)	93	Bread	38
Banana	74	Cabbage (red)	92	Butter	16
Blueberries	85	Carrots	87	Chicken	64
Cantaloupe	90	Cauliflower	92	Crackers	4
Cherries	81	Celery	95	Honey	20
Cranberries	87	Cucumber	96	Jam	28
Grapes	81	Eggplant	92	Milk	89
Grapefruit	91	Lettuce	96	Shortening	0
Orange	87	Peas	79	Steak	50
Peach	88	Peppers	92		
Pear	84	Potato	79		
Pineapple	87	Radish	95		
Plum	85	Spinach	92		
Raspberries	87	Zucchini	95		
Strawberries	92	Tomato (red)	94		
Watermelon	92	Tomato (green)	93		

Note
Values are expressed as percentages by weight.

Summary

- Minerals occur freely in nature, in the water of rivers, lakes, and oceans, and in the soil. The root system of plants absorbs minerals and they eventually become incorporated into the tissues of animals that consume plants.
- Minerals come from plant and animal sources, and their bioavailability is affected by interactions with other minerals, vitamins, and other dietary components, such as fibers, phytates, oxylates, and tannins.
- Minerals are divided into major minerals, or those needed in the diet in amounts greater than 100 mg per day, and trace minerals, or those required by the body in an amount of 100 mg or less per day.
- A balanced diet generally provides adequate mineral intake, except in some geographic locations lacking specific minerals (e.g., iodine and selenium).
- Minerals function in a variety of ways in the body. For example, calcium and phosphorous are vitally important for the structure and strength of bones and teeth; iodine is a component of the thyroid hormones which regulate metabolic rate; and chromium plays a role in regulating blood glucose levels.
- Many minerals participate in chemical reactions by serving as co-factors. They are also required for energy metabolism, nerve function, and muscle contraction. In addition, the electrolytes such as sodium and chloride, and potassium are essential for maintaining a proper fluid distribution across the body's different compartments.
- Over- or under-consumption of certain minerals has been linked to the development of certain chronic conditions. For example, a diet low in iron results in anemia that reduces oxygen-carrying capacity; a diet high in sodium increases blood pressure and thus leads to hypertension; and an inadequate consumption of calcium contributes to osteoporosis.
- Water forms the greatest component of the human body, making up 50 to 70 percent of the body's weight (about 10 gallons, or 40 liters). It is consumed in beverages and food, and a small amount is produced by metabolism.

- Body water is distributed between intracellular and extracellular compartments. The body regulates the distribution of water by adjusting the concentration of solutes in each compartment. This is due to osmosis whereby water always moves from a region of lower solute concentration to a region of higher solute concentration.
- Water plays an active role in many processes, including hundreds of chemical reactions. Water also helps keep the body at a constant temperature, even when the environment is very cold or very hot. In addition, water provides protection, helps remove waste products, and serves as an important solvent and lubricant.
- The recommended total water intake per day is 2.7 liters (11 cups) for adult women and 3.7 liters (15 cups) for adult men. Water needs can also be calculated based on energy requirements; that is, the greater the energy requirement, the greater the water needs. Adults need about 1 ml of water per kilocalorie of energy requirement, or about 2 to 3 liters per day. Water needs can be increased by variations in activity, environment, and diet.

Case study: nutrition and bone health

Michelle is a 19-year-old sophomore in college. She is a strict vegetarian. She became a near-vegan (consumes some fish) at the age of 12 when she stopped eating meat and most dairy products on urging from her mother who had been a vegan for her entire adult life. Michelle is now concerned that her diet may be deficient in vitamins and minerals. Michelle has also started smoking, and her only activity is practice for the frisbee club, which occurs once a week. Michelle's typical diet consists of oatmeal mixed with water, an apple, and a cup of fruit juice for breakfast. At lunch, she eats pasta with vegetables, bread with olives, and a soft drink. In the afternoon, she buys a snack cake or candy bar from the vending machine. For dinner, she has pasta or breads along with mixed vegetable salad, milkshake, one ounce of mixed nuts, and another soft drink. For the evening snack, she often eats cookies along with hot tea or water.

Questions

- What nutrients are low in Michelle's typical diet?
- Which of Michelle's lifestyle factors contribute to the increased risk of osteoporosis?
- What changes to her current diet could reduce the risk of osteoporosis?
- What bone assessment test would you recommend for Michelle?

Review questions

1 Describe the function of water in the body. What is the recommended water intake for adults?
2 What is a mineral? What is the difference between major and trace minerals?
3 How do sodium and potassium function in the body? What types of foods contribute the most sodium to our diet? What types of foods are good sources of potassium?
4 What are the major health concerns associated with an overconsumption of sodium?
5 Calcium and phosphorus are the first and second abundant minerals, respectively. What are the specific functions associated with each mineral? What function do these minerals have in common?
6 What role does iron play in the body? Describe the symptoms of iron deficiency-related anemia.
7 Identify a mineral that functions as an antioxidant.

8 What hormone needs iodine for its production?
9 What is the function of zinc in the body? What are the best food sources for zinc?
10 Why does selenium decrease the need for vitamin E?
11 Explain why a deficiency of copper can contribute to anemia.
12 Define the term "osmosis." If plasma becomes hypertonic, what will happen to the red blood cells? Why?
13 Explain how water moves across intestinal walls via osmosis.

Suggested reading

1 Appel LJ, Brands MW, Daniels SR, Karanja N, Elmer PJ, Sacks FM, American Heart Association (2006) Dietary approaches to prevent and treat hypertension: a scientific statement from the American Heart Association. *Hypertension*, 47: 296–308.
This article represents an official view of the American Heart Association toward the dietary approaches to preventing and treating hypertension. It discusses multiple dietary factors affecting blood pressure and provides recommendations as to how one's diet may be modified to lower blood pressure.
2 Kohrt WM, Bloomfield SA, Little KD, Nelson ME, Yingling VR, American College of Sports Medicine (2004) American College of Sports Medicine Position Stand: physical activity and bone health. *Medical Science Sports Exercise*, 36: 1985–1996.
This official document released by the American College of Sports Medicine summarizes the current literature that supports the role physical activity plays in maximizing bone mass in various groups of individuals, including children, adults, and the elderly.
3 Shirreffs SM, Maughan RJ (2000) Rehydration and recovery of fluid balance after exercise. *Exercise and Sport Sciences Reviews*, 28: 27–32.
Restoration of fluid balance after exercise-induced dehydration avoids the detrimental effects of a body water deficit on subsequent exercise performance and physiological function. This article discusses various key issues in restoring fluid balance, including the consumption of a volume of fluid greater than that lost in sweat and the replacement of electrolyte losses, particularly sodium.

Glossary

Bone remodeling degradation and resynthesize of bone.
Cretinism a condition characterized by symptoms such as mental retardation, deaf mutism, and growth failure due to deficiency in thyroid hormone.
Cupric an oxidized form of copper (Cu^{2+}).
Cuprous a reduced form of copper (Cu^{+}).
Cytochromes heme-containing protein complexes that function in the electron transport chain.
Electrolyte A substance that dissociates into ions in solution and acquires the capacity to conduct electricity. Sodium, potassium, chloride, calcium, and phosphate are examples of electrolytes.
Extracellular fluid body water found outside cells.
Ferric iron an oxidized form of iron (i.e., Fe^{3+}).
Ferrous iron a reduced form of iron (i.e., Fe^{2+}).
Fluorosis a health condition caused by a person receiving too much fluoride during tooth development.
Goiter a condition associated with an enlarged thyroid gland.
Heme iron a type of iron found mainly in animal protein such as hemoglobin in blood and myoglobin in muscle.

Hemoglobin the iron-containing protein found in red blood cells, which function to transport oxygen.

Hydroxyapatites solid mineral crystals formed by osteoblasts taking up free calcium and phosphorous.

Hypertension a blood pressure of 140/90 mmHg or greater.

Hypertonic a condition of having a higher osmotic pressure than a particular fluid, typically a body fluid or intracellular fluid.

Hypokalemia a condition of lower-than-normal blood potassium concentrations.

Hypotonic a condition of having a lower osmotic pressure than a particular fluid, typically a body fluid or intracellular fluid.

Interstitial fluid the body water found between cells.

Intracellular fluid body water found inside cells.

Ion a charged atom or molecule because of unequal number of electrons and protons.

Iron deficiency anemia a common type of anemia and a condition in which blood lacks adequate hemoglobin and thus healthy red blood cells.

Isotonic a condition in which concentrations of electrolytes are similar between both sides of the cell membrane.

Major minerals minerals needed in the diet in amounts greater than 100 mg per day or present in the body in amounts greater than 0.01 percent of the body weight.

Myoglobin the iron-containing protein found in muscle cells that functions to transport oxygen.

Non-heme iron a type of iron found mainly in vegetables, legumes, and wholegrains.

Osmosis the movement of water molecules across a partially permeable membrane from an area of high water potential (low solute concentration) to an area of low water potential (high solute concentration).

Osteoblasts a type of bone cell responsible for bone formation.

Osteoclasts a type of bone cell that removes bone tissue.

Osteopenia a moderate loss of bone mass that can lead to osteoporosis.

Specific heat the amount of energy it takes to increase the temperature of 1 gram of a substance by 1°C.

Tetany a condition in which muscles tighten and become unable to relax.

Trace minerals minerals required by the body in an amount of 100 mg or less per day or present in the body in an amount of 0.01 percent or less of body weight.

7 Digestion and absorption

Contents

Key terms

- Allergic reaction
- Antigen
- Appendix
- Appetite
- Arteries
- Arterioles
- Bolus
- Cecum
- Cephalic phase
- Chemoreceptors
- Cholecystokinin (CCK)
- Chyme
- Coenzymes
- Colon
- Condensation
- Constipation
- Diarrhea
- Duodenum
- Energy of activation
- Enteric endocrine system
- Enteric nervous system
- Enzymes
- Epiglottis
- Gallstones
- Gastric inhibitory protein
- Gastric phase
- Gastrin
- Gastrointestinal tract
- Heartburn
- Hemorrhoids
- Hepatic portal circulation
- Hunger
- Hydrolysis
- Ileum
- Immunoglobulins
- Intestinal phase
- Irritable bowel syndrome
- Jejunum
- Lacteals
- Lactose intolerance
- Lower esophageal sphincter
- Lumen
- Mechanoreceptors
- Microvilli
- Pepsin
- Peptic ulcers
- Peristalsis
- Probiotic
- Pyloric sphincter
- Rectum
- Satiety
- Secretin
- Segmentation
- Sphincter
- Substrates
- Ulcer
- Veins
- Venules
- Villi

Chemical basis related to digestion and absorption

Proper food intake provides an uninterrupted supply of energy and tissue-building chemicals to sustain life. For exercise and sports participants, the ready availability of specific nutrients takes on added importance because physical activity increases energy expenditure and the need for tissue repair and synthesis. Nutrient uptake by the body involves complex physiological and metabolic processes that usually progress unnoticed for a lifetime. Hormones and enzymes work in concert throughout the digestive tract, at proper levels of acidity–alkalinity, to facilitate the breakdown of complex nutrients into simpler and absorbable subunits. Substances produced during digestion are absorbed through the thin lining of the small intestine and pass into blood and lymph. Self-regulating processes within the digestive tract usually move food along at a slow rate to allow for its complete absorption, yet rapidly enough to ensure timely delivery of its nutrient.

Hydrolysis and condensation

Hydrolysis reactions digest or break down complex molecules such as carbohydrates, lipids, and proteins into simpler forms that the body absorbs and assimilates. During the

decomposition process, chemical bonds split by the addition of hydrogen ions (H^+) and hydroxyl ions (OH^-), the constituents of water, to the reaction by-products. Examples of hydrolysis reactions include the digestion of starches and disaccharides to monosaccharides, protein to amino acids, and lipids to glycerol and fatty acids. A specific enzyme catalyzes each step in the breakdown process. For breaking down disaccharides, the enzymes are lactase, sucrase, and maltase for lactose, sucrose, and maltose, respectively. The enzyme lipase degrades the triglycerides molecule by adding water, thereby cleaving the fatty acids from their glycerol backbone. During protein degradation, protease enzymes accelerate amino acid release when the addition of water splits the peptide bonds. All of these examples represent catabolism, which in some cases may result in a release of energy. Figure 7.1a illustrates the hydrolysis reaction for the disaccharide sucrose to its end-product molecules of glucose and fructose.

The reactions illustrated for hydrolysis also occur in the opposite direction known as **condensation**. In this reverse process (shown in Figure 7.1b), a hydrogen atom is cleaved from one molecule and a hydroxyl group is removed from another. As a result, while a compound of maltose is synthesized, a water molecule is also formed. The condensation reactions are also referred to as an anabolic process during which individual components of the nutrients bind together in condensation reactions to form more complex molecules. Condensation reactions also apply to protein synthesis. In this process, as a peptide bond is formed from two amino acids, a water molecule is created from a hydroxyl ion cleaved from one amino acid and hydrogen ion from the other amino acid. For lipids, water molecules form when a glycerol binds with three fatty acids to form a triglyceride molecule.

Enzymes: the biological catalysis

The speed of cellular chemical reactions is regulated by catalysts called **enzymes**. Enzymes are proteins that play a major role in digestion as well as in the regulation of metabolic pathways in the cell. Enzymes do not cause a reaction to occur, but simply

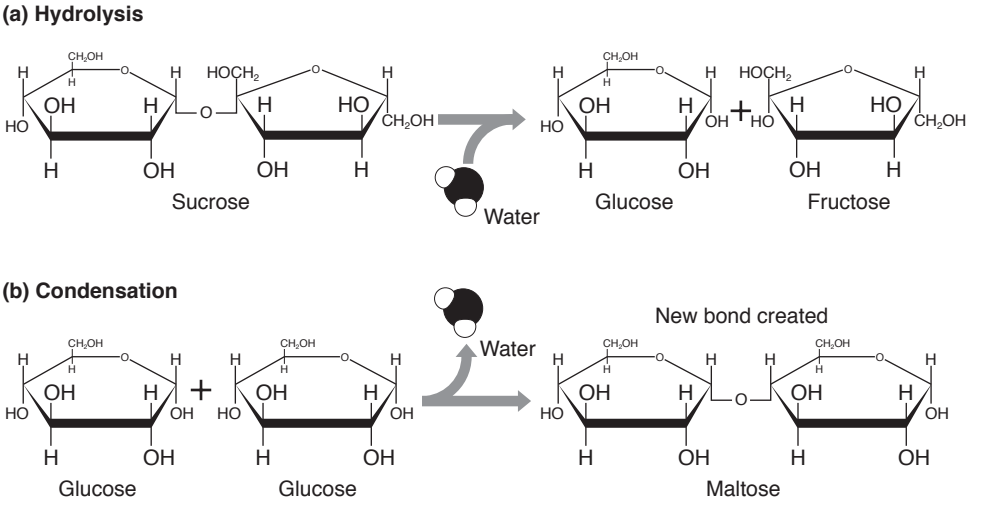

Figure 7.1 Hydrolysis reaction of the disaccharide sucrose to the end-product molecules glucose and fructose (a) and condensation reaction of two glucose molecules forming maltose (b)

regulate the rate or speed at which the reaction takes place. The great diversity of protein structures enables enzymes to perform highly specific functions. Enzymes only affect reactions that would normally take place but at a much slower rate. Enzymes do not change the nature of the reaction nor its final result.

Chemical reactions occur when the reactants have sufficient energy to proceed. The energy required to initiate chemical reactions is called the **energy of activation**. Enzymes work as catalysts by lowering the energy of activation. By reducing the energy of activation, enzymes increase the speed of chemical reactions and therefore increase the rate of product formation.

Enzymes possess the unique property of not being altered by the reactions they affect. Consequently, the turnover of enzymes in the body remains relatively slow and they are continually reused. A typical mitochondrion may contain up to 10 billion enzyme molecules, each carrying out millions of operations within a brief time. During exercise, enzyme activity increases enormously within the cell owing to an increase in energy demand. Enzymes make contact at precise locations on the surfaces of cell structures (e.g., mitochondria); they also operate within the structure itself. Many enzymes function outside the cell – in the bloodstream, digestive mixture, or fluids of the small intestine.

Although there is a standardized naming system for enzymes, most textbooks use common names that generally reflect the mode of operation or substance with which it interacts. Except for older enzymes such as rennin, trypsin, and pepsin, almost all enzyme names end with the suffix "ase." For example, hydrolase adds water during hydrolysis reactions, protease interacts with protein, oxidase adds oxygen to a substance. In addition, kinases are a group of enzymes that add phosphate groups to the reactants or substances with which they react. Further, dehydrogenases are enzymes that remove hydrogens from substances they catalyze. In the realm of human biology, those substances that are acted upon by enzymes are referred to as **substrates**.

The ability of enzymes to lower the energy of activation results from unique structural characteristics. In general, enzymes are large protein molecules with a three-dimensional shape. Each type of enzyme has characteristic ridges and grooves. The pockets formed from the ridges or grooves located on the enzyme are called active sites. These active sites are important because it is the unique shape of the active site that causes a specific enzyme to adhere to a particular reactant molecule or substrate. The concept of how enzymes fit with a particular substrate molecule is analogous to the idea of a lock and key (Figure 7.2). The shape of the enzyme's activity site is specific to the shape of a particular substrate, which allows the two molecules, enzyme and substrate, to form a complex known as the enzyme–substrate complex. Following the formation of the enzyme–substrate complex, the energy of activation needed for the reaction to occur is lowered, and the reaction is more easily brought to completion. This is followed by dissociation of the enzyme and product.

The "lock-and-key" mechanism offers a protective function so that only the correct enzyme activates the targeted substrate. Consider the enzyme hexokinase, which accelerates a chemical reaction by linking with a glucose molecule. As a result of the action of this enzyme, a phosphate group transfers from adenosine triphosphate (ATP) to a specific binding site on one of the glucose's carbon atoms. Once the two binding sites join to form a glucose–hexokinase complex, the substrate begins its stepwise degradation (controlled by other specific enzymes) to form less complex molecules during energy metabolism.

The temperature and hydrogen ion concentrations of the reactive medium dramatically affect enzyme activity. Each enzyme performs its maximum activity at a specific pH. The optimum pH of an enzyme usually reflects the pH of the body fluids in which it

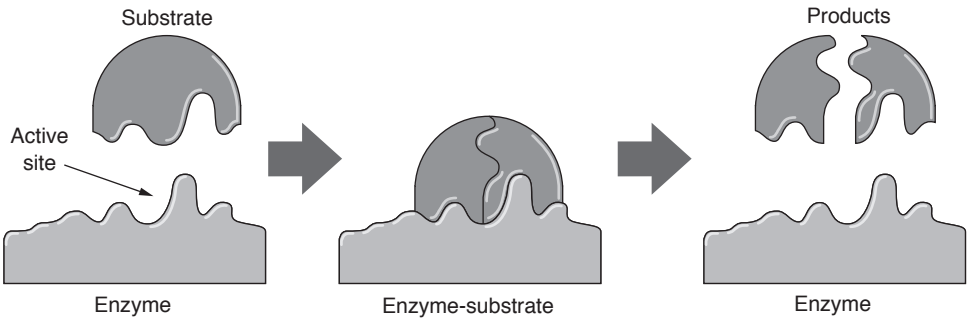

Figure 7.2 Sequences and steps in the "lock and key" mechanism of enzyme action

bathes. For some enzymes, optimal activity requires a relatively high acidity level. For example, the protein-splitting enzyme pepsin released by the stomach is most active in hydrochloric acid, whereas trypsin released by the pancreas functions more effectively on the alkaline side of neutrality. Increases in temperature generally accelerate enzyme reactivity. As the temperature rises above 40 to 50°C, enzymes may become denatured and therefore lose their function permanently.

Some enzymes require activation by additional ions and/or smaller organic molecules termed **coenzymes**. These complex non-protein substances facilitate enzyme action by binding the substrate with its specific enzyme. The metallic ions iron and zinc function as coenzymes, as do the B vitamins or their derivatives. Oxidation-reduction reactions use the B vitamins riboflavin and niacin, while other vitamins serve as transfer agents for groups of compounds in metabolic processes. A coenzyme requires less specificity in its action than an enzyme because the coenzyme affects a number of different reactions. It can serve as a temporary carrier of intermediary products in the reaction. For example, the coenzyme nicotinamide adenine dinucleotide (NAD) forms NADH to transport hydrogen atoms and electrons that split from food fragments during energy metabolism. The electrons then pass to special transporter molecules in another series of chemical reactions that ultimately deliver the electrons to molecule oxygen.

The digestive system: an overview

The foods and beverages we consume, for the most part, must undergo extensive alteration by the digestive system to provide us with usable nutrients. The digestive system provides two major functions: (1) digestion, the physical and chemical breakdown of food, and (2) absorption, the transfer of nutrients from the digestive tract into the blood or lymphatic circulatory systems. Carbohydrates, lipids, and proteins are digested and absorbed as sugars, fatty acids, and amino acids, respectively. Some substances, such as water, can be absorbed without digestion, whereas others, such as dietary fibers, cannot be digested by humans and therefore cannot be absorbed. These unabsorbed substances pass through the digestive tract and are excreted in the feces.

The digestive system is made up of the digestive tract and accessory organs (Shier *et al.* 2010). The digestive tract, more commonly known as the **gastrointestinal tract** or alimentary tract, may be thought of as a hollow tube that runs from the mouth to the anus (Figure 7.3). Organs that make up the gastrointestinal tract include the mouth, pharynx, esophagus, stomach, small intestine, and large intestine. The inside of the tube that these organs form is called the **lumen**. Food within the lumen of the

gastrointestinal tract has not been absorbed and is therefore technically still outside of the body. Only after food is transferred into the cells of the intestine by the process of absorption is it actually inside the body. The accessory organs participate in digestion but are not part of the gastrointestinal tract, and include the salivary glands, pancreas, liver, and gall-bladder (Figure 7.3). The accessory organs release their secretions needed for the process of digestion into ducts, which empty into the lumen of the gastrointestinal tract.

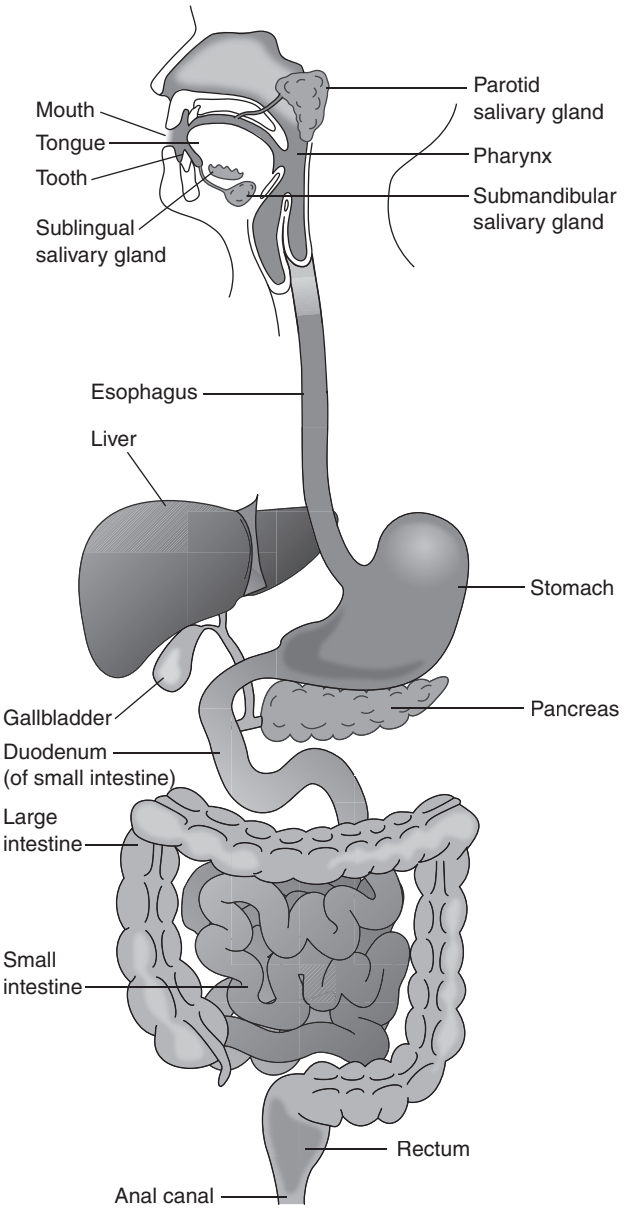

Figure 7.3 Gastrointestinal tract and accessory organs of the digestive system

Source: Shier *et al.* (2010). Used with permission.

The amount of time between the consumption of food and its elimination as solid waste is called transit time. It takes approximately 24 to 72 hours for food to pass from mouth to anus. Many factors affect transit time, such as composition of diet, illness, certain medications, physical activity, and emotions. Bands of smooth muscle called sphincters act like one-way valves, regulating the flow of the luminal contents from one organ to the next. The gastrointestinal tract has several sphincters, which are often named according to their anatomical locations. For example, the ileocecal sphincter is between the ileum, the last segment of the small intestine, and the cecum, the first portion of the large intestine.

Organization of the gastrointestinal tract

The digestive tract contains our major tissue layers: the mucosa, submucosa, muscular layer, and serosa. Each tissue layer contributes to the overall function of the gastrointestinal tract by providing secretions, movement, communication, and protection.

Mucosa

The innermost lining of the digestive tract, called the mucosa, consists mainly of epithelial cells and carries out a variety of digestive functions. The mucosa, often called the mucosal lining, produces secretions needed for digestion such as enzymes, hormones, and mucus. The digestive system produces and releases a variety of substances and secretions referred to collectively as digestive juices, some of which are relatively acidic. Because mucosal cells are continuously exposed to harsh digestive secretions within the gastrointestinal tract, their life span is a mere two to five days. Once the mucosal epithelial cells wear out, they slough off and are replaced by new cells.

Submucosa

A layer of connective tissue called the submucosa surrounds the mucosal layer. The mucosal layer contains a rich supply of blood-vessels, which nourish the inner mucosal layer and the next outer muscular layer. In addition to blood-vessels, the submucosa contains lymphatic vessels, which are filled with fluid called lymph. Lymph transports fluid away from the body tissues and aids in the circulation of fat. The submucosa also contains a network of nerves called the submucosal plexus, which regulates the release of gastrointestinal secretions from cells making up the mucosal lining.

Muscular layer

Moving outward from the submucosa, the next layer in the gastrointestinal tract is the two layers of smooth muscle organized as an outer longitudinal and an inner circular layer. Located between these two muscle layers is the myenteric plexus, a network of nerves that control the contraction and relaxation of the muscle. Such contraction and relaxation promotes mixing of the food mass with digestive secretions and keeps food moving through the entire length of the gastrointestinal tract.

Serosa

The serosa is the outermost layer that encloses the gastrointestinal tract and consists of connective tissue and provides overall support and protection. In particular, the serosa

secretes a fluid that lubricates the digestive organs, preventing them from adhering to one another. In addition, much of the gastrointestinal tract is anchored within the abdominal cavity by mesentery, a membrane that is continuous with the serosa.

Gastrointestinal motility and secretions

The term motility refers to the mixing and propulsion of material by muscular contractions in the gastrointestinal tract. These movements result from the contraction and relaxation of circular and longitudinal muscle in the muscular layer. There are two types of movement in the gastrointestinal tract: **segmentation** and **peristalsis**. Segmentation occurs when circular muscles in the small intestine move the food mass back and forth, thereby increasing the contact between food particles and digestive secretions. Peristalsis involves rhythmic, wave-like muscle contractions that propel food along the entire length of the gastrointestinal tract. The contraction of circular muscles behind the food mass causes the longitudinal muscle to shorten. When the longitudinal muscles lengthen, the food is propelled forward. Peristalsis is similar to the motion as exhibited when an earthworm moves.

Gastrointestinal secretions are important for digestions and protections of the gastrointestinal tract, and include water, acid, electrolytes, mucus, salts, enzymes, bicarbonate, and other substances (Table 7.1). For example, mucus forms a protective coating that lubricates the mucosal lining. Digestive enzymes are biological catalysts that facilitate chemical reactions which break down complex food particles. More specifically, digestive enzymes catalyze hydrolysis reactions as mentioned above, which break down chemical bonds by adding water. As a result, molecules such as starch and protein are broken down into smaller components so that they may be absorbed across the mucosal lining. Organs that release digestive secretions include the salivary glands, stomach, pancreas, gall-bladder, small intestine, and large intestine. In fact, approximately 7 liters of secretions, most of which is water, are released daily into the lumen of the gastrointestinal tract. Fortunately, the body has a "recycling" system that enables much of this water to be reclaimed.

Table 7.1 Important gastrointestinal secretions and their functions

Secretion	*Source*	*Function*
Saliva	Mouth	Partially digesting starch with salivary amylase, lubricating food for swallowing
Mucus	Mouth, stomach, small intestine, large intestine	Protecting GI tract, lubricating food as it travels through the GI tract
Enzyme	Mouth, stomach, small intestine, pancreas	Breaking down complex foods into smaller particles for absorption
Acid	Stomach	Promoting digestion of protein among other functions
Bile	Liver (stored in gall-bladder)	Assisting fat digestion in the small intestine by suspending fat in water
Bicarbonate	Pancreas, small intestine	Neutralizing stomach acid when food mix reaches the small intestine
Hormones	Stomach, small intestine, pancreas	Stimulating production of acid, enzyme, bile, and bicarbonate, regulating peristalsis and food movement, and influencing the desire to eat

Regulation of gastrointestinal motility and secretions

Gastrointestinal motility and secretions are carefully regulated by neural and hormonal signals. These involuntary regulatory activities ensure that complex food particles are physically and chemically broken down and food mass moves along the gastrointestinal tract at the appropriate rate. The gastrointestinal tract has three regulatory control systems. The intestinal and the central nervous system provide neural control, and the intestinal endocrine system provides hormonal control.

Intestinal nervous system

The gastrointestinal tract has its own local nervous system called the **enteric nervous system**. The enteric nervous system receives information from other nerves called sensory receptors located within the gastrointestinal tract. There are two kinds of sensory receptors, **chemoreceptors** and **mechanoreceptors**, each monitoring conditions and changes related to digestive activities. Chemoreceptors detect changes in the chemical composition of the luminal contents, whereas mechanoreceptors detect stretching or distension in the walls of the gastrointestinal tract. The presence of food in the tract can stimulate both chemo- and mechanoreceptors. Information from both kinds of sensory receptors is relayed to the enteric nervous system, which responds by communicating with a variety of muscles and glands. In return, muscles and glands carry out the appropriate response to help with digestion, such as an increase in peristalsis and/or release of digestive secretions.

Central nervous system

The intestinal nervous system controls digestive functions at the local level. However, the gastrointestinal tract also communicates with the central nervous system. The central nervous system consists of the brain and spinal cord, which receive and respond to sensory input from the gastrointestinal tract. The function of both the enteric and central nervous systems keeps the digestive system and the brain in close communication. This is why sensory and emotional stimuli can affect one's digestive function. For example, the sight, smell, or thought of food stimulates gastrointestinal motility and secretion. Similarly, emotional factors such as fear, sadness, anger, anxiety, and depression can cause gastrointestinal distress.

Intestinal endocrine system

The gastrointestinal tract consists of many different types of cell, some of which are hormone-producing cells referred to collectively as the **enteric endocrine system**. Hormones produced by these cells are important in providing communication in the body. Enteric hormones, which act as chemical messengers, are released into the blood in response to chemical and physical changes in the gastrointestinal tract. This information is then communicated to other organs, alerting them to the impending arrival of food. Similar to neural signals, hormones also influence the rate at which food moves through the gastrointestinal tract and the release of gastrointestinal secretions. In addition to regulating gastrointestinal motility and secretion, some enteric hormones communicate with appetite centers in the brain, and thus influence the desire to eat. The four major enteric hormones are gastrin, secretin, cholecystokinin, and gastric inhibitory protein. These hormones are released from different digestive organs. As such, the specific role of each of these hormones will be discussed later in the chapter as each organ is introduced.

Digestion and absorption processes

The digestive system is composed of six separate organs; each organ performs one or more specific jobs, but all of them work in a "coordinated" fashion. Because most foods we consume are mixtures of carbohydrates, lipids, and proteins, the physiology of the digestive system is designed to allow the digestion of all those components without competition among them. The following sections of this chapter will trace a meal through all of these digestive organs, from food entering the mouth to its elimination as waste products from the large intestine.

The mouth

The mouth is the entry point for food into the digestive tract. It performs many functions in the digestion of foods. Besides chewing food to reduce it to smaller particles, the mouth also senses the taste of foods we consume. The tongue, through the use of its taste-buds, identifies foods on the basis of their specific flavors. Sweet, sour, salty, and bitter constitute our primary taste sensations. In addition to these basic tastes, a compound found in the seasoning monosodium glutamate (MSG) delivers an additional taste sensation. The presence of food in the mouth stimulates the release of saliva from the salivary glands located internally at the sides of the face and immediately below and in front of the ears. Saliva contains the enzyme salivary amylase, which begins the digestion of carbohydrate. Salivary amylase can break down the long chains of starch into smaller segments of sugars. Saliva also lubricates the upper gastrointestinal tract and moistens the food so that it can be further tasted and easily swallowed.

Another important function performed by the mouth is chewing, which is often referred to as part of physical digestion. Digestive enzymes can act only on the surface of food. Therefore, chewing is important because it breaks food into small pieces, increasing the surface area in contact with digestive enzymes. Chewing also breaks apart fiber that traps nutrients in some foods. Remember from Chapter 5 that more vitamins are found in the peel or outer region of fruits and vegetables that are rich in fiber. In this context, fewer nutrients will be absorbed without effective chewing. Adult humans have 32 teeth designed for biting, tearing, grinding, and crushing foods. Thus, missing or decayed teeth can interfere with the proper digestion of food. Tooth decay or cavities is caused by acid produced when bacteria break down carbohydrates.

The tongue, made primarily of muscle, assists in chewing and swallowing. As food mixes with saliva, the tongue manipulates the food mass, pushing it up against the hard, bony palate of the mouth. As we prepare to swallow, the tongue directs the soft, moist mass of food, now referred to as a **bolus**, toward the back of the mouth, an area known as the pharynx. The pharynx is the shared space between the mouth and the esophagus which connects the nasal and oral cavities. This phase of swallowing is under voluntary control, but once the bolus reaches the pharynx the involuntary phase of swallowing begins.

The esophagus

During the involuntary phase of swallowing, the soft palate rises, blocking the entrance to the nasal cavity. This helps guide the bolus into the esophagus. The esophagus is a long tube that connects the pharynx with the stomach. Near the pharynx is a flap of tissue called the **epiglottis** which prevents the bolus of swallowed food from entering the trachea. During swallowing, food lands on the epiglottis, which folds it down to cover the opening of the trachea. Breathing also stops automatically. These responses ensure

that swallowed food will only travel down the esophagus. If food travels down the trachea instead, choking may occur. The esophagus is a narrow, muscular tube that passes through the diaphragm, a muscular wall separating the abdomen from the cavity where the lungs are located. At the top of the esophagus, nerve fibers release signals to tell the gastrointestinal tract that food has been consumed. This then results in an increase in gastrointestinal muscle action known as peristalsis. Continual waves of muscle contraction followed by muscle relaxation force the food down the digestive tract from the esophagus.

To move food from the esophagus into the stomach, food must pass through a **sphincter**, a muscle that encircles the tube of the digestive tract and acts as a valve. When muscle contracts, the valve is closed. The **lower esophageal sphincter**, located between the esophagus and the stomach, normally prevents food from moving back out of the stomach. Heartburn occurs when some of the acidic stomach content leaks out of the stomach into the esophagus, causing a burning sensation. Vomiting is the result of a reverse peristaltic wave that causes the sphincter to relax and allows food to pass upward out of the stomach toward the mouth.

The stomach

The stomach is an expended portion of the gastrointestinal tract that can hold up to 4 cups or 1 liter of food for several hours until all the food is able to enter the small intestine. Stomach size varies individually and may be reduced surgically as a medical treatment. While in the stomach, the bolus is mixed with highly acidic stomach secretions to form a semi-liquid food mass called **chyme**. The mixing of food in the stomach is aided by an extra layer of smooth muscle in the stomach wall. As mentioned earlier, most of the gastrointestinal tract is surrounded by two layers of muscle; however, the stomach contains a third layer, enabling more powerful contractions that thoroughly churn and mix the stomach contents. Acidic secretions in the stomach help convert inactive digestive enzymes into their active form, partially digest food protein, and make dietary minerals soluble so that they may be absorbed. Following a meal, the stomach contents are emptied into the small intestine over the course of one to four hours. The **pyloric sphincter**, located at the base of the stomach, controls the rate at which the chyme is released into the small intestine. Some digestion takes place in the stomach, but, with the exception of some water and alcohol, very little absorption takes place here.

The stomach has a capacity to accommodate large amounts of food. When empty, the stomach volume is quite small – approximately one quarter of a cup. As food enters the stomach, its walls expand to increase its capacity to 4 to 8 cups or 1 to 2 liters. The ability to expand to this extent is due to the interior lining of the stomach, which is folded into convoluted pleats call rugae. Like an accordion, the rugae unfold and flatten, allowing the stomach to expand as it fills with food. The stretching of the stomach walls triggers mechanoreceptors to signal to the brain that the stomach is becoming full. In turn, the brain causes hunger to diminish, prompting a person to stop eating. The ability to recognize and respond to these internal cues is an important component of body weight regulation.

Stomach or gastric secretions are regulated by both nervous and hormonal mechanisms, as discussed earlier in this chapter. Signals from three different sites – the brain, stomach, and small intestine – stimulate or inhibit gastric secretion. Gastric secretion may be divided into three phases: cephalic, gastric, and intestinal. The **cephalic phase** occurs before food enters the stomach. During this phase, the smell, sight, or taste of food causes the brain to send nerve signals that increase gastric secretion. This prepares the stomach to receive and digest food that enters. The **gastric phase** begins when food enters the stomach. The presence of food in the stomach causes gastric secretion by

stretching local nerves, by signaling to the brain, and by stimulating the secretion of the hormone **gastrin** from the upper portion of the stomach. Gastrin triggers the release of gastric juice, which is produced by gastric glands in the lining of the stomach. One of the components of gastric juice is hydrochloric acid. This strong acid stops the activity of salivary amylase and helps begin the digestion of protein. It also serves to kill most bacteria present in food. Another component of gastric juice is pepsinogen. When pepsinogen is exposed to the acidity of the stomach, it is converted into its active form called **pepsin**, which breaks down protein into shorter chains of amino acids called polypeptides. The protein of the stomach wall is protected from the acid and pepsin by a thick layer of mucus. If the mucus layer is penetrated or destroyed, acid and pepsin can damage the inner lining of the stomach, resulting in a condition called **peptic ulcers**. A peptic ulcer is erosion in the lining of the stomach or the first part of the small intestine called the duodenum. One of the leading causes of stomach ulcers is acid-resistant bacteria that infect the lining of the stomach and thus destroy the mucosal layer (McManus 2000). The **intestinal phase** of gastric secretion begins with the passage of chyme into the small intestine. During this phase, stomach motility and secretion decreases to ensure that the amount of chyme entering the small intestine does not exceed the ability of the small intestine to process it. This phase also involves the action of the pyloric sphincter that regulates the rate at which chyme is released into the small intestine.

The rate of gastric emptying, or the rate at which food leaves the stomach, is influenced by several factors, including the volume, consistency, and composition of chyme. For example, large volumes of chyme increase the force and frequency of peristaltic contractions, which in turn increase the rate of gastric emptying. Thus, large meals leave the stomach at a fast rate compared to small meals. The consistency of food (i.e., liquid versus solid) also affects the rate of gastric emptying. Because the opening of the pyloric sphincter is small, only fluids and small particles (<2 mm in diameter) can pass through. Solid foods take more time to liquefy than fluid and, therefore, remain in the stomach for longer. Finally, the nutrient composition of the chyme also influences gastric emptying. A high-fat meal will stay in the stomach the longest. This is because the presence of fat in chyme causes the small intestine to release a hormone called **gastric inhibitory protein**. This hormone slows the rate of gastric emptying, enabling the small intestine to prepare for the task of fat digestion.

The small intestine

The small intestine is the primary site of chemical digestion and nutrient absorption. It is a narrow tube about 20 feet in length. It is divided into three segments. The first 12 inches are the **duodenum**, the next 8 feet are the **jejunum**, and the last 10 feet are the **ileum**. In addition to chyme, the duodenum receives secretions from the gall-bladder via the common bile duct. The pancreas also releases its secretions into the small intestine. Pancreatic juice is released into the pancreatic duct, which eventually joins the common bile duct. The cells lining the small intestine also secrete enzymes that are involved in the digestion of smaller sugars (e.g., disaccharides) and polypeptides into single sugar units and amino acids, respectively.

The pancreas secretes pancreatic juice, which contains bicarbonate ions and digestive enzymes. The bicarbonate ions neutralize the acid in chyme, making the environment in the small intestine neutral rather than acidic as it is in the stomach. This neutral environment allows enzymes from the pancreas and small intestine to function. The digestive enzymes from the pancreas include pancreatic amylase, pancreatic lipase, and trypsin, a protein-digesting enzyme. These enzymes continue the job of digesting carbohydrates, lipids, and proteins that began in the mouth and stomach.

The gall-bladder secretes bile, but this substance is produced in the liver. Bile is a watery solution that consists primarily of cholesterol, bile acids, and a pigment that gives bile its characteristic yellowish-green color. Once bile is formed, it is transported to the gall-bladder, where it is stored. Bile is necessary for fat digestion and absorption. Bile acts like a detergent, dispersing large globules of fat into smaller droplets. These smaller droplets allow pancreatic lipase to more efficiently access and digest fat molecules. Without bile, it would be difficult for enzyme lipase to make direct contact with the chemical bonds. Once the lipids are absorbed, bile is reabsorbed through the ileum and returned to the liver via the hepatic portal vein. This process enables the liver to recycle many of the constituents that make up bile. Only 5 percent of the bile escapes into the large intestine and is lost in the feces.

As in the stomach, the lining of the small intestine contains hormone-producing endocrine cells. These cells release the enteric hormones **secretin**, **cholecystokinin (CCK)**, and gastric inhibitory protein in response to conditions within the small intestine. Secretin signals to the pancreas to secrete bicarbonate ions and stimulates the liver to secrete bile into the gall bladder. CCK signals to the pancreas to secrete digestive enzymes and causes the gall bladder to contract and empty its contents into the duodenum via the common bile duct. As mentioned earlier, gastric inhibitory protein slows the rate of stomach motility that empties its chyme into the small intestine. Together, these enteric hormones work cooperatively to ensure that digestion and absorption in the small intestine are rapid yet effective. The roles of these and other enteric hormones in the process of digestion are summarized in Table 7.2.

The process of digestion physically and chemically liberates nutrients in food, so that nutrients are now ready to be absorbed. The small intestine is the primary site of absorption for virtually all nutrients, including water, vitamins, minerals, and the products of carbohydrate, lipid, and protein digestion (Table 7.3). The physical structure of the small intestine is very important to the body's ability to digest and absorb the nutrients it needs. In addition to its length, the small intestine has two other structural features that facilitate absorption. First, the intestinal walls are arranged in circular and spiral folds which increase surface area in contact with nutrients. Second, its entire inner lining is covered with finger-like projections called **villi**, and each of these villi is covered with tiny **microvilli**, often referred to as brush borders (Figure 7.4). The combined folds, villi, and microvilli in the small intestine increase its surface area 600 times beyond that of a simple tube. Each villus contains a blood-vessel and a lymph vessel, which are located only one cell layer away from the nutrients in the lumen of the small intestine. Lymph vessels are known as **lacteals** and can absorb large particles such as the products of fat digestion. Nutrients must cross the mucosal layer to reach the bloodstream or lymphatic system being used by the body.

The transfer of nutrients into the mucosal cells, or what is referred to as nutrient absorption, takes place by passive and active transport mechanisms: simple diffusion, facilitated diffusion, and active transport (Figure 7.5).

- Passive diffusion: When the nutrient concentration is higher in the lumen of the small intestine than in the absorptive cells, the difference in the nutrient concentration drives the nutrient into the absorptive cells through diffusion. Fats, water, fat-soluble vitamins, and some minerals are absorbed by passive diffusion.
- Facilitated diffusion: Some nutrients cannot pass freely across cell membranes even though there is a favorable concentration gradient, and they require a carrier protein to drive them into the absorptive cells. This process is called facilitated diffusion. Fructose is one example of a compound that makes use of such carrier protein to allow for absorption.

Table 7.2 Hormones that regulate digestion

Hormones	*Source*	*Stimulus for secretion*	*Major action*
Gastrin	Stomach	• Foods entering the stomach • Stretch of the stomach wall • Alcohol and caffeine • Smell, taste, sight	• Stimulates gastric motility • Stimulates gastric emptying • Stimulates gastric secretions
Secretin	Duodenum	• Arrival of acidic chyme into the small intestine	• Inhibits gastric motility • Inhibits gastric secretions • Stimulates release of pancreatic juice containing bicarbonate ions and enzymes
Cholecystokinin	Duodenum	• Arrival of partially digested fat and protein into the small intestine	• Stimulates gall bladder to contract and release bile • Stimulates releases of pancreatic juice
Gastric inhibitory protein	Duodenum	• Arrival of fat and glucose into the small intestine	• Inhibits gastric motility and emptying • Inhibits gastric secretions

Table 7.3 Major sites of absorption along the gastrointestinal tract

Organ	*Primary nutrients absorbed*
Stomach	• Alcohol (20%) • Water (minor amount)
Small intestine	• Calcium, magnesium, iron, and other minerals • Glucose • Amino acids • Fats • Vitamins • Water (70–90% of total) • Alcohol (80% of total) • Bile acids
Large intestine	• Sodium • Potassium • Some fatty acids • Some minerals • Some vitamins • Water (10–30% of total)

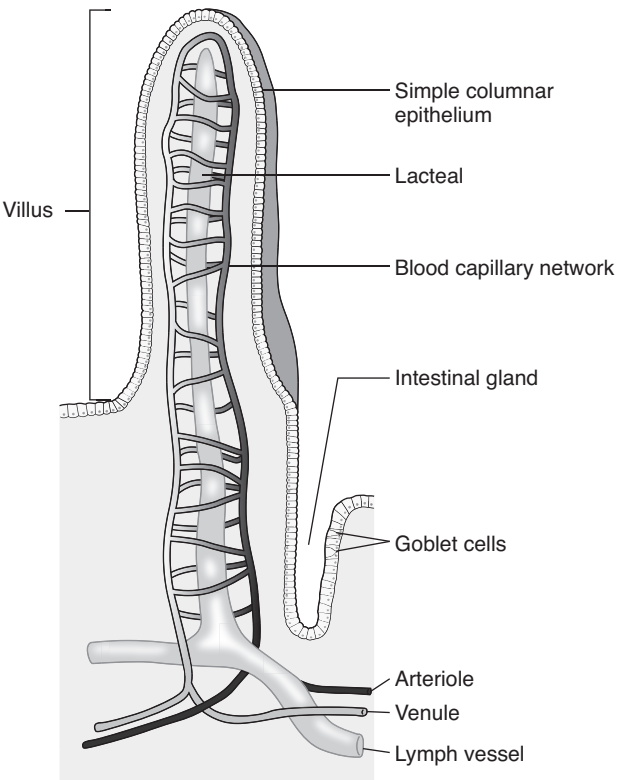

Figure 7.4 The small intestine contains folds, villi, and microvilli, which increase the absorptive surface area

Source: Shier *et al.* (2010). Used with permission.

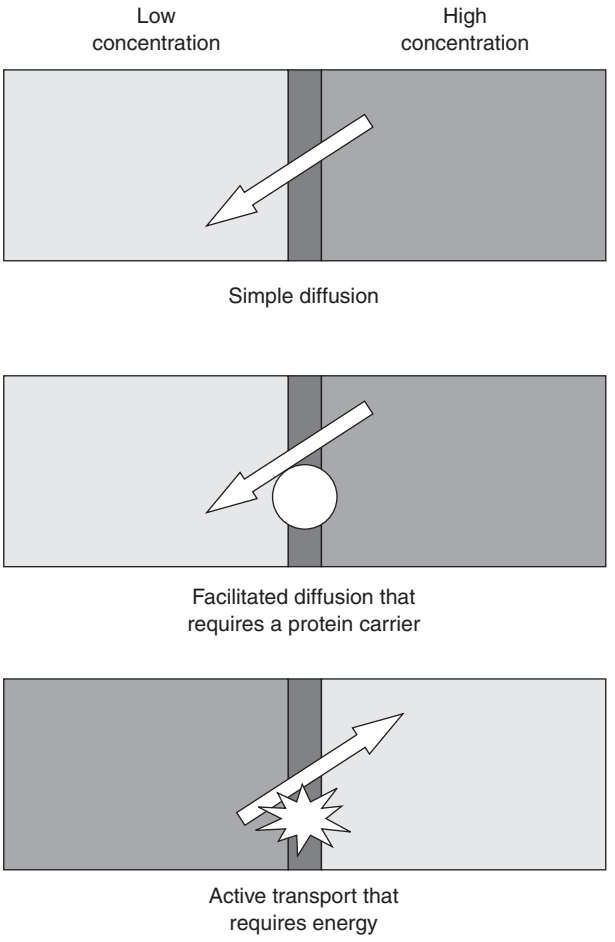

Figure 7.5 Nutrients are absorbed from the lumen into absorptive cells by simple diffusion, facilitated diffusion, and active transport

- Active transport: In addition to the need for a carrier protein, some nutrients also require energy input to move from the lumen of the small intestine into the absorptive cells. This mechanism makes it possible for cells to take up nutrients even when they are consumed in low concentrations. Glucose as well as most amino acids is absorbed by this mechanism.

The large intestine

Components of chyme that are not absorbed in the small intestine pass into the large intestine, which includes the **cecum**, **colon**, and **rectum**. The cecum, the first portion of the large intestine, is a short, saclike structure with an attached appendage consisting of lymphatic tissue called the **appendix**. On occasion, trapped materials can cause the appendix to become inflamed which may necessitate an appendectomy – the surgical removal of the appendix. The ileocecal sphincter that separates the ileum from the cecum regulates the intermittent flow of material from the ileum to the cecum. The colon, which makes up most of the large intestine, is shaped like an inverted letter U

and consists of the ascending colon, the transverse colon, and the descending colon. Following the descending colon is the rectum, which terminates at the anal canal, the segment of the large intestine that leads outside of the body.

When the contents of the small intestine enter the large intestine, the materials left bear little resemblance to the food originally eaten. Under normal circumstances, only a minor amount (5 percent) of carbohydrates, lipids, and proteins escape absorption to reach the large intestine. The large intestine differs from the small intestine in that there are no villi or digestive enzymes. The absence of villi means that little absorption takes place in the large intestine compared with the small intestine. Nutrients absorbed from the large intestine include water, some fatty acids, some vitamins, and the minerals sodium and potassium (Table 7.3). Peristalsis in the large intestine is slower than that in the small intestine. Water, nutrients, and fecal matter may spend 24 hours in the large intestine, in contrast to the 3 to 5 hours it takes for chyme to move through the small intestine. This slow movement favors the growth of bacteria. Unlike the small intestine, the large intestine wall has mucus-producing cells. The mucus secreted by these cells functions to hold the feces together and to protect the large intestine from the bacterial activity within it.

The large intestine is home to a high population of bacteria. Whereas the stomach and small intestine have some bacterial activity, the large intestine is the organ most heavily colonized with bacteria. In fact, over 500 species of bacteria may be found in the large intestine. The number and type of bacteria in the human colon has recently become a subject of great interest. Research has shown that intestinal bacteria play a significant role in the maintenance of health, especially health of the colon. For example, certain bacteria can synthesize small amounts of B vitamins and vitamin K, some of which will be absorbed. These higher levels of beneficial organisms have also been found to reduce the activity of disease-causing bacteria. Foods containing certain micro-organisms, such as lactobacilli, are attracting a lot of attention. The term **probiotic** is used for these micro-organisms because once consumed, they take up residence in the large intestine and lead to certain health benefits, such as improving immunity and intestinal tract health (Madsen 2001). The probiotic micro-organisms may be found in certain kinds of milk and yogurt as well as in pill forms that are made commercially available.

Materials not absorbed are excreted as waste products in the feces. The amount of water in the feces is affected by fiber and fluid intake. Fiber retains water, so when adequate fiber and fluid are consumed, feces will have a high water content and are easily passed. However, when material moves too quickly through the colon for sufficient water to be reabsorbed, diarrhea may occur. Diarrhea is considered beneficial when it allows the body to eliminate harmful or irritating materials quickly. However, prolonged diarrhea may result in excessive loss of fluids and electrolytes from the body, which can lead to serious complications such as dehydration. Conversely, when inadequate fiber or fluid is consumed or too much water is removed, feces will become hard and dry, and constipation may result.

Paths of absorbed nutrients

Absorbed materials are delivered to the body cells by the cardiovascular system, which consists of the heart and blood-vessels. The path by which nutrients enter the bloodstream varies with the nutrient. Amino acids from protein, simple sugars from carbohydrate, and the water-soluble products of fat such as glycerol are absorbed directly into the bloodstream. The products of fat digestion such as fatty acids that are not water soluble are taken into the lymphatic system before entering the blood.

The cardiovascular system consists of the heart and a closed network of a vascular system through which blood is circulated. The heart is considered the engine of the cardiovascular system. It is a muscular pump with two circulatory circuits – one that delivers the blood to the lungs and one that delivers the blood to the rest of the body. The blood vessels that transport the blood toward the heart are called **veins**, and those that transport blood away from the heart are called **arteries**. As arteries carry blood away from the heart, they branch many times to become smaller and smaller. The smallest arteries are called **arterioles**. Arterioles then branch to form capillaries that have a thin wall and narrow diameter, and are permeable to many small particles. A capillary network marks the end of the arterial blood flow to the cell and the beginning of the venous blood flow away from the cell and back to the heart. In the capillaries of the gastrointestinal tract, water soluble nutrients diffuse across the wall of capillaries into the bloodstream that flows into the small veins, the **venules**, which converge to form larger and larger veins for return to the heart. These nutrients are then pumped out of the heart into arteries to be delivered to various parts of the body.

The intestine and liver have a unique circulatory arrangement called the **hepatic portal circulation**. In this circulation, water-soluble nutrients such as amino acids and sugars cross the mucosal cells of the villi and enter capillaries. These capillaries merge to form venules at the base of the villi. The venules then merge to form larger veins, which eventually form the hepatic portal vein. The hepatic portal vein then transports blood directly to the liver, where absorbed nutrients are processed. This arrangement gives the liver first access to the nutrient-rich blood leaving the small intestine. Nutrients taken up by the liver can be stored or may undergo metabolic reactions. The liver also releases nutrients into the blood, which are then circulated to other parts of the body. In addition to nutrients, substances that are potentially harmful to the body such as alcohol are also taken up and detoxified by the liver.

The liver acts as a gatekeeper between substances absorbed from the intestine and the rest of the body (Vander *et al.* 2001). Some nutrients are stored in the liver, some are changed into different forms, and others are allowed to pass through unchanged. Based on the immediate needs of the body, the liver decides whether individual nutrients will be stored, used, or delivered directly to the cells. For example, the liver modulates blood glucose by storing or releasing the absorbed glucose depending on the level of blood glucose concentrations. The liver is also responsible for the synthesis or breakdown of protein and fats. It modifies the products of protein degradation to form molecules that can be safely transported to the kidneys for excretion. The liver also helps protect the body from toxins or to remove cholesterol from the blood and use it to make bile.

Another major structure in a close relationship with digestion and absorption is the lymphatic system. The lymphatic system consists of a network of lymph vessels and lymph nodes, and lymph organs such as the spleen that provide protection to the body. Fluid that has accumulated in tissues drains into the lymphatic system where it is filtered past a collection of infection-fighting cells. The cleansed fluid is then returned to the bloodstream.

Unlike water-soluble nutrients, most lipids cannot easily enter blood capillaries because they are too large and insoluble in water. Consequently, molecules such as triglycerides, fatty acids, and fat-soluble vitamins are taken up by lacteals, which are more permeable than blood capillaries. Lacteals, the smallest lymph vessels, drain these absorbed nutrients into larger lymph vessels. These larger lymph vessels from the intestine and most other organs of the body further drain into the thoracic duct, which empty into the bloodstream near the neck region. Thus, nutrients that are absorbed via lacteals do not pass the liver before entering the blood.

Factors affecting food intake and choice

We need nutrients to survive, but we eat food, not nutrients. There are hundreds of food choices to make and hundreds of reasons for making them. Each of these choices contributes to our total nutrient intake. Some foods are rich in protein and minerals, others in vitamins and phytochemicals. Most of us understand that nutrition is important to our health, yet people don't want to give up their favorite foods and they don't want to eat foods they don't like. Our food choices are primarily affected by hunger and appetite. They may also be influenced by what is available to us, where we eat, what is within our budget, which is compatible with our lifestyle, what is culturally acceptable, what mood we are in, and what we think we should eat.

Hunger and appetite

Hunger and appetite are the two drives that influence our desire to eat. They differ dramatically. **Hunger** is considered biological in origin and is controlled by internal body mechanisms. For example, as nutrients are processed by the stomach and small intestine, these organs send signals to the liver and brain to reduce further food intake. **Appetite**, on the other hand, is considered psychological in origin and is controlled by external food choice mechanisms. For example, your appetite is intensified as you see a tempting dessert or smell fresh popcorn in the movie theater. We eat in response to hunger. However, what, when, and how much we eat are also affected by appetite, which is not necessarily related to hunger. Fulfilling either or both drives by eating sufficient food normally brings on a state of **satiety**, a feeling of fullness and satisfaction, which halts our desire to continue eating.

Role of the hypothalamus

The hypothalamus, a region of the brain, mediates the effect of hunger and appetite and helps regulate satiety (Figure 7.6). Signals to eat or stop eating can be external, originating from environment, or they can be internal, originating from the gastrointestinal tract, circulating nutrients, or higher centers in the brain. External factors that stimulate eating include the sight, taste, and smell of food, the time of day, culture and social gathering, the appeal of the foods available, and ethnic and religious rituals. We eat lunch at noon out of social convention, often not because we are hungry. We eat turkey on Thanksgiving because it is a tradition. We eat cookies or cinnamon rolls while walking through the mall because the smell entices us to buy them. Likewise, external factors such as religious dietary obligations or negative experiences associated with certain foods can signal us to stop eating. In addition, our knowledge of and belief in nutrition and body weight and image can also influence our eating behavior. For example, what we think of as "healthy foods" often direct our food purchase, and some people select certain foods and supplements that they believe will improve their physical appearance or performance.

Internal signals that promote hunger and satiety originate both before and after foods are consumed. The simplest type of signal about food intake comes from local nerves in the walls of the stomach and small intestine that sense the volume and pressure of the food and send a message to the brain to either start or stop eating. The presence of food in the gastrointestinal tract also triggers the release of gastrointestinal hormones such as cholecystokinin, which causes satiety. Absorbed nutrients may also send information to the brain to modulate food intake. Circulating levels of nutrients, including glucose, fatty acids, amino acids, and ketones, are monitored by the brain and may trigger signals to eat or not to eat. Nutrients taken up by the brain may affect the

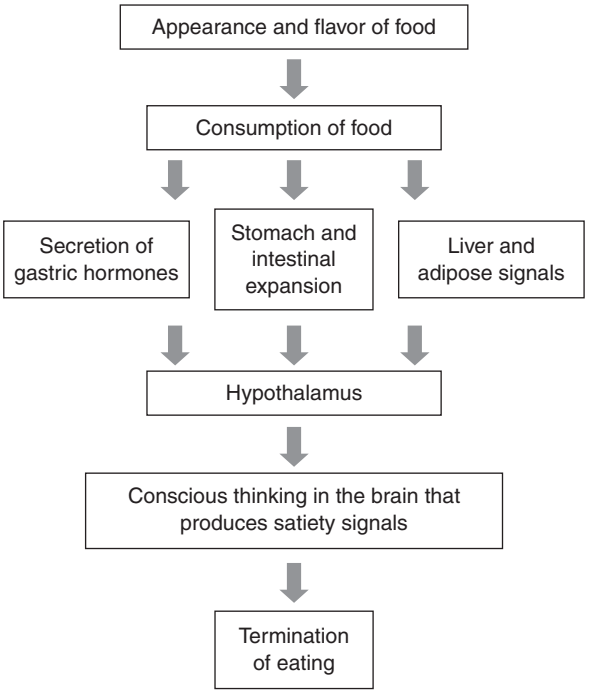

Figure 7.6 Process of satiety

neurotransmitter concentrations, which then affect the amount and types of nutrients consumed. For example, when brain serotonin is low, carbohydrates are craved, but when it is high, proteins are preferred. The pancreas is also involved in food intake regulation because it releases insulin, which triggers a feeling of fullness and, as a result, decreases the drive to eat.

Psychological stress

Psychological factors may also affect eating behavior. Psychological distress may come from events in the external environment, but processing of these events occurs in the brain cortex. The effect that emotions have on appetite depends on the individual. Some people eat for comfort and to relieve stress. Others may lose their appetite when they become emotional or distressed. A depressed person may choose to eat chocolates rather than to call a friend. A person who has returned home from an exciting evening out may unwind with a late-night sandwich. These people may find emotional comfort, in part, because foods can influence the brain's chemistry.

Overall, daily food intake is a complicated mix of biological and social influences. It means so much more to us than nourishment and it reflects much of what we think about ourselves.

Immune function of the digestive system

The gastrointestinal tract plays an important role in protecting the body from infection by foreign invaders. The lumen of the gastrointestinal tract is outside of the body and

much of it is heavily populated with potentially pathogenic micro-organisms. Thus, it is important that the immune system establishes and maintains a strong presence at this mucosal boundary. Indeed, the digestive tract is heavily laden with lymphocytes, macrophages, and other cells that participate in immune responses. The cells of the intestines form an important barrier to invading substances or **antigens**. The cells are packed closely together, producing a physical barrier to micro-organisms. If an invading substance does get past the intestinal cells, it will then be confronted by the action of the immune related cells. These immune cells trigger the production of **antibodies**, such as **immunoglobulins**, which are specialized proteins that function to counteract antigens. Immunoglobulins can bind to the invading substances, thereby preventing them from entering the bloodstream.

Nutrient deficiencies can weaken the mucosal membrane so that foreign invaders can more easily enter the body and cause infections. Two common results of undernutrition related to an impaired immune system are diarrhea and bacterial infections of the bloodstream. Nutrients that have proven effective in protecting the health of the intestinal tract are proteins, vitamin A, vitamin B6, vitamin B12, vitamin C, folate, and zinc.

The immune system is a defense mechanism that protects us from many invaders. However, the response of the immune system to a foreign substance is also responsible for **allergic reaction**. An allergic reaction occurs when the immune system produces antibodies in response to a substance, called an **allergen**, that is present in our diet or environment. For example, a food allergy occurs when proteins absorbed from food are seen as foreign which trigger an immune response. Symptoms due to food allergy include hives, itching, flushing, swelling of the lips, tongue and roof of the mouth, and breathing difficulty or anaphylaxis. The most common sources of food allergens are peanuts, tree nuts (such as walnuts, pecans, and cashews), shellfish (such as shrimp and lobster), fish, milk, eggs, wheat, and soy.

Common problems with digestion and absorption

Each of the organs and processes of the digestive system is necessary for the proper digestion and absorption of food. However, this fine-tuned organ system can develop problems. As discussed above, many factors influence gastrointestinal function. The central nervous system exerts a strong influence through diverse neural-endocrine connections with different digestive organs. Emotional state can also affect digestive function in various degrees. For example, many individuals experience intestinal cramping and a queasy stomach under stressful conditions such as a “big date” or “big game.” Some individuals get an “upset stomach” at the sight of their own blood, and it is well known that emotional stress contributes to the production of gastric abnormalities. Recent evidence suggests that most gastrointestinal problems can be treated with a healthy diet and regular exercise. For example, regular exercise enhances gastric emptying, with a concomitant reduction in the incidence of liver disease, gallstones, colon cancer, and constipation.

Problems associated with any digestive organ or process can inhibit the ability to obtain adequate nutrients and thus adversely affect nutritional status. For example, dental problems may make it difficult to chew, limiting the types of food that can be consumed and reducing contact between nutrients in food and digestive enzymes. Pancreatic problems can limit the availability of enzymes needed to digest fat and proteins, and liver or gall-bladder problems can interfere with fat absorption. The following section provides a brief description of some of the more common digestive abnormalities. The more we know about these conditions, the more likely it is that we can prevent or lessen them.

Lactose intolerance

Lactose intolerance is a condition that often begins after early childhood. It can lead to symptoms of abdominal pain, gas, and diarrhea after consuming lactose especially when eaten in a large amount. Another form of the problem, namely secondary lactose intolerance, is a temporary condition in which the production of enzyme lactase decreases in response to other conditions such as diarrhea. The symptoms of lactose intolerance include gas, abdominal bloating, cramps, and diarrhea. The bloating and gas are caused by bacterial fermentation of lactose in the large intestine. The diarrhea is caused by undigested lactose in the large intestine as it draws water from the circulatory system into the large intestine.

In the United States, approximately 25 percent of adults show signs of decreased lactose digestion in the small intestine (Lee and Krasinski 1998). Many of them are Asian Americans, Africa Americans, and Latino/Hispanic Americans, and the occurrence increases as people age. It is considered that this digestive problem is due to a genetic mutation occurring in regions that rely on milk and dairy products as a main food source, allowing those individuals (mostly in Northern Europe and the Middle East) to retain the ability to maintain a high production of enzyme lactase.

Bacteria in the large intestine can break down lactose. Therefore, those with mild lactose intolerance symptoms can still tolerate a small amount of milk (i.e., half to one cup), especially when consumed with meals. Combining lactose-containing foods with other foods helps because certain properties of foods can have positive effects on the rate of digestion. For example, fat in a meal slows digestion, which then leaves more time for lactase to produce its action. Hard cheese and yogurt are more easily tolerated than milk because much of the lactose is lost in the production process, and the bacteria cultures in yogurt can digest the lactose when they are broken apart in the small intestine. If necessary, products such as low-lactose or lactose-free milk or lactase pills may be used to assist those who are lactose intolerant.

Ulcers

A peptic **ulcer** can occur when the lining of the esophagus, stomach, or small intestine is eroded by the acid secreted by the stomach cells. As the stomach lining deteriorates in ulcer development, it loses its protective mucus layer, and the acid further erodes the stomach tissue. Acid can also damage the lining of the esophagus and the first part of the small intestine, the duodenum. The typical symptom of an ulcer is pain about two hours after eating. This is because the stomach acid released for digestion irritates the ulcer after most of the meal has moved from the site of ulcer.

The further risk associated with an ulcer is that it will damage the entire stomach and intestinal wall. Consequently, the gastrointestinal contents can spill into the body cavities, causing massive infection. In addition, an ulcer may erode a blood-vessel, leading to substantial blood loss. For these reasons, it is important not to ignore the early warning signs of ulcer development, including a burning near the stomach that occurs immediately following a meal or wakes you up at night. Other signs and symptoms of ulcers are weight loss, nausea, vomiting, loss of appetite, and abdominal bloating.

It has long been thought that the major cause of ulcers is an excessive production of acid. As such, neutralizing and curtailing the secretions of stomach acid has been the common treatment choice. However, it has been recognized recently that although acid is still a significant player in ulcer formation, the principle causes of ulcer disease are (1) infection of the stomach by acid-resistant bacteria such as *Helicobacter Pylori*, heavy use of anti-inflammatory drugs such as aspirin, and other disorders that cause excessive acid production

in the stomach. Stress is considered as a predisposing factor for ulcers, especially if the person is infected with *Helicobacter Pylori* or has certain anxiety disorders. Cigarette smoking is also known to cause ulcers or increase ulcer complications such as bleeding.

Heartburn

Heartburn occurs when the sphincter between the esophagus ad stomach relaxes involuntarily, allowing the stomach's contents to flow back into the esophagus. Unlike the stomach, the esophagus has no protective mucus lining so acid back flow can damage it and cause pain. Other symptoms may also include nausea, gagging, coughing, or hoarseness. The recurrent and therefore more serious form of the problem is called gastroesophageal reflux disease (GERD), which is characterized by the occurrence of such symptoms two or more times a week. Typically, the gastroesophageal sphincter should be relaxed only during swallowing, but in individuals with GERD it is relaxed at other times as well.

Heartburn or GERD occurs in approximately 60 percent of athletes and more frequently during exercise than at rest. The mechanisms for why this condition is more prevalent among athletes or during exercise are not well understood. The many speculations include: (1) reduced gastric motility; (2) delayed gastric emptying; (3) relaxation of the lower esophageal sphincter; (4) increased intra-abdominal pressure, and (5) increased mechanical stress by the bouncing of gastrointestinal organs. Athletes involved in predominantly anaerobic sports such as weight lifting experience most frequent acid reflux and heartburn, while these symptoms are found to be less frequent and milder in runners and cyclists.

Heartburn sufferers should follow the general recommendations of (1) waiting about two hours after a meal before lying down; (2) avoiding post-prandial exercise; (3) reducing meal size and fat consumption, and (4) elevating the head of the bed. For occasional heartburn, quick relief can be found with over-the-counter medications, such as antacids. Prescription medications are available for treating more persistent heartburn or GERD. If the proper medications are not effective at controlling the problem, surgery may be needed to strengthen the weakened esophageal sphincter.

Constipation

Constipation refers to a delay in stool movement through the colon. As fluid is increasingly absorbed during the extended time the feces stay in the large intestine, they become dry and hard. Constipation may result when people regularly inhibit their normal bowel reflexes for long periods. Another common cause is the regular consumption of a diet high in fat and low in water and fiber content. Muscle spasms of an irritated large intestine can also slow the movement of feces and contribute to constipation. In addition, calcium and iron supplements and medications such as antacids may also cause constipation.

Eating foods with plenty of fiber such as fruits and wholegrain breads and cereals along with drinking adequate fluids is the best approach to treating mild cases of constipation (Müller-Lissner *et al.* 2005). Fiber stimulates peristalsis by drawing water into the large intestine and forming a bulky, soft stool. Dried fruits are a good source of fiber and therefore help stimulate the bowel. In addition, people with constipation may need to develop a habit that allows the same time each day for a bowel movement. For more severe constipation, laxatives as well as various other medications may be used to lessen the problem. These medications work by either stimulating peristaltic muscle contraction or by drawing more water to produce a bulky stool.

Hemorrhoids

Hemorrhoids are painful, swollen veins in the lower portion of the rectum or anus. This is often because blood-vessels in this region are subject to intense pressure, especially during pregnancy and after childbirth, obesity, prolonged sitting, violent coughing or sneezing, or straining during bowel movements, particularly with constipation. Such an increase in pressure causes the veins to bulge and expand, making them painful, particularly when sitting. Hemorrhoids may be located inside the rectum (internal hemorrhoids), or they may develop under the skin around the anus (external hemorrhoids). Internal hemorrhoids occur just inside the anus, at the beginning of the rectum. External hemorrhoids occur at the anal opening and may hang outside the anus.

Hemorrhoids are a common digestive disorder. By the age of 50, about half of adults have had to deal with the itching, discomfort, and bleeding that can signal the presence of hemorrhoids. Pressure from prolonged sitting or exertion is often enough to trigger the symptoms, although diet, lifestyle, and possibly heredity play a role. Pain may be lessened by applying warm, soft compresses or sitting in a tub of warm water for 15 to 20 minutes. Dietary recommendations are the same as those for treating constipation, emphasizing the need to consume adequate fiber and water. Symptoms can also be alleviated by using over-the-counter creams and suppositories, although these medications should only be used for a short time because long-term use can damage the skin.

Diarrhea

Diarrhea is the condition of having three or more loose or liquid bowel movements per day. It is very common and usually not serious, and is accompanied by symptoms of abdominal bloating or cramps, thin or loose stools, a sense of urgency to have a bowel movement, and nausea and vomiting. Many people will have diarrhea once or twice a year. It typically lasts for two to three days and can be treated with over-the-counter medicines. Diarrhea may also occur as part of irritable bowel syndrome or other chronic diseases of the large intestine. Most cases of diarrhea result from infections caused by bacteria and viruses, which can cause the intestinal cells to secrete rather than absorb fluid. Other causes include eating foods that upset the digestive system, allergies to certain foods, certain medications, intestinal diseases, malabsorption, and alcohol abuse. Diarrhea may also follow constipation, especially for people who have irritable bowel syndrome.

Distance runners are more susceptible to diarrhea. Possible causes include fluid and electrolyte and altered colonic motility. However, such acute exercise-induced diarrhea is considered physiological, meaning that it does not produce dehydration or electrolyte imbalances, and tends to improve with fitness levels.

Treatment of diarrhea generally requires drinking lots of fluids during the affected stage and reducing ingestion of the poorly absorbed substance if that is a cause. To alleviate symptoms, those who have diarrhea may choose fruit juice without pulp, soda without caffeine, chicken broth without the fat, tea with honey, and sports drinks. Over-the-counter medicines as liquids or tablets are also available for treating mild diarrhea. Prompt treatment within 24 hours is especially important for infants and older individuals, as they are more susceptible to the effects of dehydration associated with diarrhea. Adults who suffer from diarrhea for more than seven days should be examined by a physician, as it can be a symptom of more serious intestinal disease.

Irritable Bowel Syndrome

Irritable Bowel Syndrome (IBS) is a functional bowel disorder characterized by chronic abdominal pain, discomfort, bloating, and alteration of bowel habits in the absence of any detectable cause. The two IBS forms include (1) diarrhea predominant, and (2) constipation predominant. In most cases the symptoms are relieved by bowel movements. The exact cause of IBS is unknown. The most common theory is that IBS is a disorder of the interaction between the brain and the gastrointestinal tract (Andresen and Camilleri 2006). In other words, those who suffer from IBS have altered intestinal peristalsis coupled with a decreased pain threshold for abdominal distension. IBS may begin following an infection, a stressful life event, or onset of maturity without any other medical indicators.

IBS affects 20 percent of the adult population and is more common in younger women than in younger men. In older adults, the ratio is closer to 50:50. Approximately 50 percent of patients with IBS also report psychiatric symptoms of depression and anxiety.

No cure has been found for IBS, but many options are available to treat the symptoms. For many people, careful eating reduces IBS symptoms. For example, dietary fiber may lessen IBS symptoms, particularly constipation. Wholegrain breads and cereals, fruits, and vegetables are good sources of fiber. High-fiber diets keep the colon mildly distended, which may help prevent spasms. Dietary fiber also keeps water in the stool, thereby preventing hard stools that are difficult to pass. This diet intervention, however, may not help with lowering pain or decreasing diarrhea. Other lifestyle therapies include: (1) consuming meals of a smaller size; (2) avoiding dairy products; (3) stress management, and (4) regular exercise. IBS may also be treated with medications used to decrease constipation, diarrhea, and intestinal muscle spasm.

Gallstones

Gallstones are pieces of solid material that develop in the gall bladder when substances in the bile, primarily cholesterol, form crystal-like particles. They may be as small as a grain of sand or as large as a golf ball. Gallstones are caused by a combination of factors, including inherited body chemistry, body weight, gall-bladder motility, and diet, with excess weight being the primary factor especially in women (Marschall and Einarsson 2007). The absence of such risk factors does not, however, preclude the formation of gallstones. Many people with gallstones have never had any symptoms. The gallstones are often discovered when having a routine X-ray, abdominal surgery, or other medical procedure. However, if a large stone blocks either the cystic duct or common bile duct, you may have a cramping pain in the middle to right upper abdomen. The pain goes away if the stone passes into the first part of the small intestine, the duodenum.

Gallstones can be treated by using medications, such as ursodeoxycholic acid, that help with dissolving the stone or by using a procedure called lithotripsy, which is a method of concentrating ultrasonic shock waves onto the stones to break them up. However, these forms of treatment are only suitable when there are a small number of gallstones. Surgical removal of the gall bladder is the most common method for treating gallstones. Gall-bladder removal has a 99 percent chance of eliminating the recurrence of gallstones. In most people, the lack of a gall bladder has no negative consequences.

Prevention of gallstones revolves around avoiding becoming overweight, especially for women. Avoiding rapid weight loss, substituting animal protein with plant protein, and following a high-fiber diet will help as well. Regular physical activity is also recommended, as is moderate to no caffeine and alcohol intake.

Summary

- Hydrolysis reactions digest or break down complex molecules such as carbohydrates, lipids, and proteins into simpler forms that the body absorbs and assimilates. The reactions for hydrolysis also occur in the opposite direction known as condensation, a process during which individual components of the nutrients bind together to form more complex molecules.
- Enzymes are proteins that play a major role in digestion as well as in the regulation of metabolic pathways in the cells. Digestive enzymes are secreted by the mouth, stomach, small intestine, and pancreas and function to facilitate the movement and breakdown of food molecules.
- The digestive system involves the gastrointestinal tract consisting of a hollow tube that begins at the mouth and continues through the esophagus, stomach, small intestine, and large intestine. It also includes accessory organs, such as the liver, gall bladder, and pancreas.
- The stomach acts as a temporary storage site for food. The muscles of the stomach mix the food into a semi-liquid mass called chyme, and gastric juice containing hydrochloric acid and pepsin begins protein digestion. Little absorption occurs in the stomach except for some water and alcohol.
- The small intestine is the primary site of nutrient digestion and absorption and consists of fingerlike projections call villi. In the small intestine, bicarbonate from the pancreas neutralizes stomach acid, and pancreatic and intestinal enzymes digest carbohydrates, fats, and proteins. The digestion of fat in the small intestine is aided by bile from the gall bladder.
- Components of chyme that are not absorbed in the small intestine pass on to the large intestine, where some water and mineral are absorbed. The large intestine is populated by bacteria that digest some of these unabsorbed materials, such as fiber, and products from bacterial breakdown of fibers and other substances are also absorbed here.
- The water-soluble products of carbohydrate, fat, and protein digestion enter the capillaries in the intestinal villi and are transported to the liver via the hepatic portal circulation. The liver serves as a processing center, storing some of the absorbed substances in the liver, converting some of them into other forms, or allowing them to pass unchanged.
- The fat-soluble products of digestion, such as fatty acids, enter lacteals in the intestinal villi. The nutrients absorbed via the lymphatic system enter the blood circulation without first passing to the liver.
- Absorption of food across the intestinal mucosa occurs by several different processes, including simple diffusion, facilitated diffusion, and active transport. Both simple and facilitated diffusion do not require energy, but depend on a concentration gradient. Active transport requires energy, but may transport nutrients against a concentration gradient.
- Hunger and appetite are the two drives that influence our desire to eat. The hypothalamus, a region of the brain, mediates the effect of hunger and appetite and helps regulate satiety.
- Signals to eat or stop eating can be external, originating from environments including sight, taste, and smell, or they can be internal, originating from the gastrointestinal tract, circulating nutrients, or higher centers in the brain.
- The lumen of the gastrointestinal tract is outside of the body and much of it is heavily populated with potentially pathogenic micro-organisms. Thus, it is important for the immune system to establish and maintain a strong presence at this mucosal boundary.

- Many of the common digestive disorders, such as heartburn constipation, and irritable bowel syndrome, can be treated with diet changes. These may include increasing fiber intake and avoiding large meals high in fat. Medications are also very helpful in many cases.

Case study: understanding the condition of lactose intolerance

Lily, a 26-year-old Asian graduate student reading biomedical engineering, had been experiencing occasional discomfort after meals. The discomfort had reached a new peak the previous Thursday evening about an hour after consuming a cheeseburger and a large chocolate milk shake. Lily spent much of the night in pain. She had abdominal cramps and diarrhea, and also felt sick to her stomach. Lily went to the clinic and saw a doctor the following day. The doctor asked Lily a number of questions and noted that Lily's discomfort seemed to be associated with dining out. Lily told the doctor that on most evenings she cooked for herself, usually preparing traditional Asian cuisine, and that she seldom experienced any discomfort after eating at home. When asked if she used very much milk or cheese when preparing meals at home, Lily told the doctor that she almost never cooked with dairy products. The doctor suspected that Lily could be lactose intolerant and told Lily that she would like to have a test performed to verify her initial diagnosis. Lily was able to be tested on that day because she had not had anything to eat or drink for two hours. At the clinic lab, Lily was given a lactose-rich fluid to drink and had her blood glucose level measured several times over the course of two hours. Later, her doctor informed Lily that her blood glucose level had not risen after drinking the lactose-rich fluid and therefore she was lactose intolerant.

Questions

- What is lactose intolerance?
- Why is this condition associated with stomach discomfort and diarrhea?
- What kinds of dietary adjustments should Lily consider in order to avoid or ease the symptoms of this condition?

Review questions

1 Define the terms (1) hydrolysis, and (2) condensation.
2 What is peristalsis?
3 How does the structure of the small intestine aid absorption?
4 Why is it important to maintain an acidic environment in the stomach?
5 How is the inner lining of the stomach protected from acid HCl? How is the small intestine protected from acidic chyme coming from the stomach?
6 Both pepsin and trypsin are enzymes involved in protein digestion. Explain the differences between the two.
7 One of the medications used to treat stomach ulcers is to inhibit gastric secretion of HCL. If such medication is used for too long, digestion of which food item will be affected. Why?
8 Explain how gastrin, secretin, cholecystokinin, and gastric inhibitory protein regulate the digestion process.
9 Cholecystokinin, leptin, and insulin are the three satiety hormones discussed in class. Where is each hormone secreted from? How do they regulate our energy intake?

10 How is the liver related to digestion and absorption? Digestion of what type of nutrient would be affected the most if the liver were severely damaged? Why?
11 How is the pancreas connected to the digestive tract? What enzymes does the pancreas produce in helping digestion?
12 Define the terms (1) passive diffusion, (2) facilitate diffusion, and (3) active transport.
13 What is "portal circulation"? What role does portal circulation play in digestion and absorption?
14 Define the terms hunger, appetite, and satiety. Explain the role of the hypothalamus in regulating hunger and satiety.
15 What are the internal and external signals that promote hunger and satiety?

Suggested reading

1 Bi L, Triadafilopoulos G (2003) Exercise and gastrointestinal function and disease: an evidence-based review of risks and benefits. *Clinical Gastroenterology and Hepatology*, 1: 345–355.
This article evaluates the effect of the different modes and intensity levels of exercise on gastrointestinal function and disease using an evidence-based approach. It provides much-needed information, as the impact of exercise on the gastrointestinal system has been conflicting.
2 Peters HP, De Vries WR, Vanberge-Henegouwen GP, Akkermans LM (2001) Potential benefits and hazards of physical activity and exercise on the gastrointestinal tract. *Gut*, 48: 435–439.
Physical activity reduces the risk of colon cancer. However, acute strenuous exercise may provoke gastrointestinal symptoms such as heartburn or diarrhea. This review describes the current state of knowledge on the hazards of exercise and the potential benefits of physical activity on the gastrointestinal tract.
3 Williams C, Serratosa L (2006) Nutrition on match day. *Journal of Sports Science*, 24: 687–697.
This article takes a practical approach in discussing how to design regular meals and dietary supplementation for a match or competition. In particular, the effect of consuming various types of carbohydrate on sports performance is discussed.

Glossary

Allergen a substance that causes an allergic reaction.
Allergic reaction the response of the immune system to a foreign substance.
Antibodies specialized proteins that function to counteract antigens.
Antigens invading substances that induce an immune response in the body.
Appendix a blind-ended tube connected to the cecum.
Appetite a neurological drive that influences one's desire to eat and is controlled by external factors such as sight, smell, hearing, and social functions.
Arteries the blood-vessels that transport the blood away from the heart.
Arterioles the smallest arteries that branch to form capillaries.
Bolus the soft, moist mass of food formed from chewing, grinding, and mixing with saliva.
Cecum the first portion of the large intestine.
Cephalic phase the time period before food enters the stomach.
Chemoreceptors sensory receptors that detect changes in the chemical composition of the luminal contents.

Cholecystokinin also referred to as CC, the hormone produced from the small intestine that signals the pancreas to secrete enzymes and causes the gall bladder to contract and empty its contents into the duodenum.

Chyme a semi-liquid food mass formed from mixing with highly acidic stomach secretions.

Coenzymes non-protein substances such as ions and/or smaller organic molecules that facilitate enzyme action.

Colon the largest section of the large intestine consisting of the ascending colon, the transverse colon, and the descending colon.

Condensation an anabolic process during which individual components of the nutrients bind together to form more complex molecules.

Constipation a delay in stool movement through the colon.

Diarrhea a condition of having three or more loose or liquid bowel movements per day.

Duodenum the first 12 inches of the small intestine.

Energy of activation the energy required to initiate chemical reactions.

Enteric endocrine system hormone-producing cells located within the gastrointestinal tract.

Enteric nervous system the local nervous system located within the gastrointestinal tract.

Enzymes a group of proteins that function to regulate the speed at which the reaction takes place.

Epiglottis a flap of tissue near the pharynx that prevents the bolus of swallowed food from entering the trachea.

Gallstones pieces of solid material that develop in the gall-bladder when substances in the bile, primarily cholesterol, form crystal-like particles.

Gastric inhibitory protein a hormone released from the small intestine that slows the rate of gastric emptying.

Gastric phase the time period that begins when food enters the stomach.

Gastrin the hormone secreted from the upper portion of the stomach that triggers the release of gastric juice, such as hydrochloric acid.

Gastrointestinal tract a hollow tube or alimentary canal that runs from the mouth to the anus.

Heartburn a condition in which the sphincter between the esophagus and stomach relaxes involuntarily, allowing the stomach's contents to flow back into the esophagus.

Hemorrhoids painful, swollen veins in the lower portion of the rectum or anus.

Hepatic portal circulation the circulatory arrangement in the abdominal cavity that drains blood from the gastrointestinal tract and spleen to capillary beds in the liver.

Hunger a neurological drive that influences one's desire to eat and is controlled by internal body mechanisms, such as the activities of the stomach and small intestine.

Hydrolysis chemical reactions that digest or break down complex molecules into simpler forms.

Ileum the last section of the small intestine, which is 10 feet long and leads to the large intestine.

Immunoglobulins specific types of antibodies.

Intestinal phase the time period that begins when chyme is passed into the small intestine.

Irritable bowel syndrome a functional bowel disorder characterized by chronic abdominal pain, discomfort, bloating, and alteration of bowel habits in the absence of any detectable cause.

Jejunum the next 8 feet of the small intestine in between the duodenum and ileum.
Lacteals lymphatic capillaries that absorb large particles such as the products of fat digestion.
Lactose intolerance a condition that leads to symptoms of abdominal pain, gas, and diarrhea after consuming lactose especially in large amounts.
Lower esophageal sphincter the sphincter located between the esophagus and the stomach that prevents foods from moving back out of the stomach.
Lumen the inside of the gastrointestinal tract.
Mechanoreceptors sensory receptors that detect stretching or distension in the walls of the gastrointestinal tract.
Microvilli tiny, hair-like folds in the plasma membrane that extend from the surface of the epithelial cells of the intestinal wall.
Pepsin the enzyme that breaks protein down into shorter chains of amino acids or polypeptides.
Peptic ulcers erosion in the lining of the stomach or the first part of the small intestine called the duodenum.
Peristalsis a type of gastrointestinal movement that involves rhythmic, wave-like muscle contractions that propel food along the entire length of the gastrointestinal tract.
Probiotics living micro-organisms that take up residence in the large intestine and provide certain health benefits.
Pyloric sphincter sphincter located at the base of the stomach that controls the rate at which the chyme is released into the small intestine.
Rectum the last section of the large intestine that follows the descending colon.
Satiety a feeling of fullness and satisfaction that halts one's desire to continue eating.
Secretin the hormone produced from the small intestine and which signals the pancreas to secrete bicarbonate ions and stimulate the liver to secrete bile.
Segmentation a type of gastrointestinal movement when circular muscles in the small intestine move the food mass back and forth.
Sphincter a muscle that encircles the tube of the digestive tract and acts as a valve.
Substrates substances or chemical compounds that are acted upon by enzymes.
Ulcer a condition where the lining of the digestive tract is eroded by the acid secreted by the stomach cells.
Veins the blood vessels that transport the blood toward the heart.
Venules the smallest veins that receive blood flow from the capillaries and converge to form larger veins for return to the heart.
Villi tiny, finger-like projections that protrude from the epithelial lining of the intestinal wall.

8 Energy and energy-yielding metabolic pathways

Contents

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Energy

Energy is required by all cells. In order for you to jump, throw, run, swim, or cycle, skeletal muscle cells must be able to extract energy from energy-containing nutrients such as carbohydrates and fats. Energy is also needed for other bodily functions such as circulation, digestion, absorption, glandular secretion, neural transmission, and biosynthesis, to just name of a few. Although the body has some energy reserves, most of its energy must be obtained through nutrition. Most cells possess chemical pathways that are capable of converting energy-containing nutrients into a biologically usable form of energy. This metabolic process is termed **bioenergetics**. During exercise, energy requirement increases, and energy provision can become critical. In fact, inability to transform energy contained in foodstuffs rapidly into biologically usable energy would limit sports performance. In athletes, carbohydrate depletion represents one of the most common causes of fatigue. On the other hand, persons with a defect in energy metabolism cannot tolerate high-intensity exercise. For example, those with McArdle's disease who have trouble with degrading muscle glycogen for energy will have impaired exercise capacity. The amount of food energy available coupled with the ability to transform the food energy into the form that is usable by body cells is what dictates how well the body responds to physical stress. As such, it is imperative to understand what energy is and how the body acquires, converts, stores, and utilizes energy.

Energy

Energy is defined as the ability to produce change and is measured by the amount of work performed during a given change. Unlike the physical properties of matter, energy cannot be defined in concrete terms of size, shape, or mass. The presence of energy is revealed only when change occurs. Energy is often reflected in exercise performance during which energy stored in macronutrients is extracted and ultimately transformed into **adenosine triphosphate** (ATP) in order to power mechanical work. The faster the energy transformation, the greater the exercise performance.

The first law of thermodynamics

The first law of thermodynamics states that the body does not produce, consume, or use up energy; it merely transforms energy from one state to another. Indeed, energy is neither created nor destroyed. It exists in many forms that can be converted from one to another. For example, it has become increasingly popular to use solar panels to convert the sun's rays or light energy into electricity. In the body, energy is first obtained from energy-containing nutrients in food and, in most circumstances, then being converted as potential energy stored in the body tissues. Via cellular respiration, this potential energy is then converted into the high-energy compound adenosine triphosphate (ATP) as well as heat. The energy in ATP is used for a variety of biological work, including muscle contraction, synthesizing molecules, and transporting substances. That energy is neither created nor destroyed during any physical and/or chemical process is one of the most important axioms of science, the law of the conservation of energy that applies to both living and not-living systems. The first law of thermodynamics may be viewed as a version of the law of the conservation of energy that is adapted for a living system.

Unit of energy

Within the biological context, energy is measured in joules (J) or kilojoules (kJ), which are units of work, or in calories (cal) or kilocalories (kcal or Cal), which are units of heat. A kJ is the amount of work required to move an object of 1 kilogram a distance of 1 meter under the force of gravity. In Europe and most parts of Asia, the J or kJ is the standard measure of energy in food and the body. However, the cal or kcal is the measure most commonly used in the United States and Canada. In theory, a kcal is the amount of heat required to raise the temperature of 1 kilogram of water by 1 degree Celsius. Any measure by kcal or kJ is 1000 times greater as compared to that by cal or J, respectively. To convert cal to J or kcal to kJ, the calorie value needs to be multiplied by 4.186, i.e., 1 cal = 4.186 J or 1 kcal = 4.186 kJ.

Potential and kinetic energy

In the area of exercise science, the form of energy that powers muscle contraction is often described as **mechanical energy**, and activities such as walking, running, swimming, jumping, and throwing require the production of mechanical energy. This form of energy is possessed by an object due to its motion or its position or internal structure. Mechanical energy can be either **kinetic energy** (energy of motion) or **potential energy** (energy of position). For example, a book on a shelf has stored potential energy. In addition, by stretching a rubber band, you give it potential energy. Kinetic energy, on the other hand, can be illustrated by individuals performing physical activity. Thinking of a gymnast who is on the balance beam, the movements and flips she performs show the kinetic energy being displayed while she is moving. When you are running, walking, or jumping, your body is also exhibiting kinetic energy. Both forms of energy can exist at the same time, but often change from one form to another. For example, the water at the top of the waterfall has stored potential energy. Once the water leaves the top of the waterfall, the potential energy is changed into kinetic energy. Within a biological system, such a transfer of energy may be exemplified as energy stored in energy-containing nutrients being released through **catabolism**, a process in which more complex substances are broken down into simpler ones. In this case, the released potential energy is transformed into kinetic energy of motion. On the other hand, **biosynthesis** may be viewed as a reverse process in which energy in one substance is transferred into other substance so that their potential energy increases.

Oxidation and reduction

The majority of chemical reactions that occur in the body involve the transfer of electrons from one substance to another. **Oxidation** is the loss of electrons during a reaction by a molecule, atom, or ion. Some elements lose electrons more easily than others. These elements are said to be easily oxidized. Generally speaking, metals, including sodium, magnesium, and iron, are easily oxidized. Elements that are more reluctant to lose electrons are not easily oxidized; they hold onto their electrons very tightly. Nonmetals, including nitrogen, oxygen, and chlorine, are not easily oxidized. On the other hand, **reduction** is any chemical reaction that involves the gaining of electrons. It refers to the molecule, atom, or ion that accepts electrons. For example, when iron reacts with oxygen it forms a chemical called rust, the common name for iron oxide (Fe_2O_3). In that example, the iron is oxidized and the oxygen is reduced.

Oxidation and reduction reactions are always coupled and are thus often regarded as **Redox**, an abbreviation for a chemical reduction–oxidation reaction. Redox reactions involve the transfer of electrons between chemical species; that is, electrons being passed from one molecule to another, resulting in the one that gains the electrons becoming reduced, and the one that loses the electrons becoming oxidized. Accordingly, the term **reducing agent** refers to the substance that donates or loses electrons as it oxidizes, whereas the substance being reduced or gaining electrons is called the **oxidizing agent**. Oxygen is not necessarily needed in such reactions, as other chemical species can serve the same function.

Chemical reactions involved in energy production in mitochondria are excellent examples of Redox. Special carrier molecules transfer oxidized hydrogen atoms and their removed electrons for delivery to oxygen so that it becomes reduced. Hydrogen atoms are derived from nutrients of carbohydrates, lipids, and proteins. Two hydrogen carriers are **nicotinamide adenine dinucleotide** (NAD), derived from the B vitamin niacin, and **flavin adenine dinucleotide** (FAD), derived from another B vitamin, riboflavin. Upon accepting hydrogen and its associated electron, NAD and FAD are reduced to become NADH and FADH, respectively. The transport of electrons by specific carrier molecules constitutes the **respiratory chain**, which represents the final pathway of aerobic metabolism. For each pair of hydrogen atoms, two electrons flow down the chain and ultimately reduce one atom of oxygen. This pathway ends when oxygen combines with hydrogen to form water. Details of the aerobic pathway are discussed later in this chapter.

Biologically usable form of energy

In a living cell, ATP is the most important carrier of the energy necessary to perform many complex functions. This energy-containing compound stores potential energy extracted from food and can yield such energy to power various biological activities via hydrolysis, a process in which a compound is split into other compounds by reacting with water. ATP is the only form of chemical energy that is convertible into other forms of energy used by living cells. As such, ATP is often regarded as energy currency. Fats and carbohydrates are the main storage forms of energy in the body. However, energy derived from oxidation of these two fuels does not release suddenly or sufficiently fast enough to meet the energy demand of those activities that are short and explosive. It is well known that energy liberation from food is a relatively complex process which is well controlled by enzymes and takes place within the watery medium of cells. But with the production of ATP, this slow energy transformation from foods is not a concern. ATP may be viewed as a temporary reservoir of energy which functions to provide instant energy to the cells whenever it is needed.

The structure of ATP consists of three main parts: (1) an adenine portion, (2) a ribose portion, and (3) three linked phosphates (Figure 8.1). The formation of ATP occurs by combining adenosine di-phosphate (ADP) with inorganic phosphate (Pi) and requires a large amount of energy. Some of this energy is stored in the chemical bond that joins ADP and Pi. During hydrolysis, adenosine triphosphatase (ATPase) catalyzes the reaction when ATP joins with water. In the degradation of one mole of ATP, the outermost phosphate bond splits and liberates approximately 7.3 kcal of free energy that is available for work. This then results in a production of ADP and Pi. In some cases, additional energy is released when another phosphate splits from ADP and this results in the production of adenosine mono-phosphate (AMP). The energy liberated during ATP breakdown transfers directly to other energy-requiring molecules. In muscle, for instance, the energy is used to energize the myosin cross-bridge, causing the muscle fiber to shorten. The splitting of an ATP molecule takes place immediately and does not need oxygen. The body can store a very limited amount of ATP. Most activities are powered by ATP mainly produced through the oxidation of carbohydrates and fats. One example where the body relies on its stored ATP is those moments of holding one's breath during a short sprint or lifting. Chemical processes in which ATP is formed from other energy fuels will be discussed in detail later in this chapter.

Energy consumption

The energy needed to fuel the body comes from the food we eat as well as the energy already stored in the body. Carbohydrates, fats, and proteins are the three energy-containing nutrients consumed regularly. Upon entering the body, these macronutrients undergo a series of hydrolytic reactions, including the digestion of starches and disaccharides to monosaccharides, protein to amino acids, and lipids to glycerol and fatty acids. These simpler forms of macronutrients are then absorbed and assimilated via the hepatic portal vein which routes blood from the capillary beds of the gastrointestinal tract into the liver. While some of these molecules are used to meet the immediate energy needs of the body, others are stored as potential energy in more complex forms, such as glycogen in muscle and liver and triglycerides in muscle and adipose tissue. The amount of energy taken in depends on the total amount of food consumed and the nutrient composition of the food.

Measurement of energy content of foods

The energy content of foods can be measured by using a bomb calorimeter, which consists of a sealed steel chamber surrounded by a jacket of water (Figure 8.2).

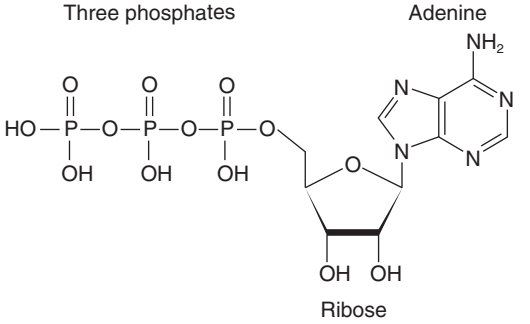


Figure 8.1 An adenosine tri-phosphate (ATP) molecule. The symbol "~" represents energy stored in the phosphate bond

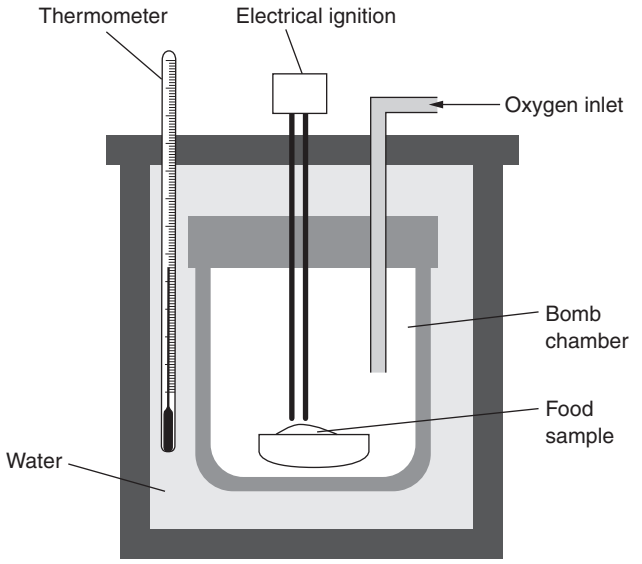


Figure 8.2 A bomb calorimeter. When dried food is combusted inside the chamber of a bomb calorimeter, the rise in temperature of the surrounding water may be used to determine the energy content of the food

A weighted amount of food (i.e., 1 g) is placed in the chamber with high oxygen pressure. The reaction is started through ignition by an electrical current. As the food combusts, heat is produced and transferred through the metal wall of the chamber, and heats the water that surrounds it. The increase in water temperature may be used to calculate the amount of energy in the food on the basis that 1 kcal is the amount of heat needed to increase the temperature of 1 kilogram of water by 1°C. For example, if the water volume surrounding the chamber was 5 L and the temperature of water rises by 2°C, then the amount of energy contained in the food was $5 \times 2 = 10$ kcal (or $10 \times 4.186 = 41.86$ kJ). If the mass of food combusted was 5 g, then energy density of the food was $10/5 = 2$ kcal/g.

This method determines quite accurately the total energy content in foods. However, it is not without its drawbacks. This technique is expensive to run and provides no information as to the composition of carbohydrates, fats, and proteins in the food combusted. Because the body cannot completely digest, absorb, and utilize all the energy in a food, caloric values from this technique are often slightly higher than the amount of energy the body can actually obtain from the food. This pertains particularly to proteins, because the body cannot oxidize the nitrogen component of amino acids, the building blocks of a protein. Consequently, nitrogen atoms combine with hydrogen to form urea to be excreted via the kidneys. Because energy is stored in the hydrogen bond, such a loss of hydrogen results in a reduction in energy of an amino acid that is available for use. Quantitatively, the energy the body can actually obtain from 1 g of protein consumed is about 4.6 kcal on average rather than 5.65 kcal as measured by the bomb calorimeter. This represents a loss of approximately 20 percent of the potential energy stored in a protein molecule. As both carbohydrates and fats contain no nitrogen, the amount of fuel the body acquires from each of these two nutrients is similar to what is determined by the bomb calorimeter.

Digestive efficiency

How much energy stored in foods can become available to the body is also affected by the efficiency of the digestive process. **Digestive efficiency**, often defined as the coefficient of digestibility, represents the percentage of ingested food digested and absorbed to serve the body's metabolic needs. A coefficient of digestibility of 50 means that only half of the energy consumed was ultimately absorbed. Since this digestive parameter provides information as to how much energy from the food consumed can actually arrive inside the body, it has become a major guiding factor in designing a dietary program for weight loss or maintenance. The coefficient of digestibility is relatively higher in both lipids and carbohydrates, reaching 90 percent and higher. However, those carbohydrate products containing dietary fiber will have lower digestibility. As such, consuming carbohydrates rich in fiber will help reduce the amount of energy available to the body. According to early data published in the USDA Handbook (Merrill and Watt 1973), for instance, the coefficient of digestibility of wheat bran carbohydrate is only 56 percent, suggesting that the body will obtain only a little over half of the energy stored in this food. Protein has a greater range of the coefficient of digestibility (i.e., 80 to 97 percent). This is due to the fact that a protein molecule may vary in terms of its constituent amino acids or its food source. In general, the coefficient of digestibility is lower in plant protein than in protein from animal sources.

Table 8.1 shows different coefficients of digestibility, heats of combustion, and net energy values for nutrients in various food groups. As shown, the average coefficients of digestibility for proteins, lipids, and carbohydrates are 92, 95, and 97 percent, respectively. The net energy values are identical to the product of the coefficient of digestibility

Table 8.1 Digestibility, heat of combustion, and net physiological energy values of dietary protein, lipid, and carbohydrate

Food group	*Digestibility (%)*	*Heat of combustion (kcal/g)*	*Net energy (kcal/g)*
Protein			
Meat and fish	97	5.65	4.27
Eggs	97	5.75	4.37
Dairy products	97	5.65	4.27
Cereals	85	5.80	3.87
Legumes	78	5.70	3.47
Vegetables	83	5.00	3.11
Fruits	85	5.20	3.36
Overall average	*92*	*5.65*	*4.05*
Lipid			
Meat and eggs	95	9.50	9.03
Dairy products	95	9.25	8.79
Vegetables	90	9.30	8.37
Overall average	*95*	*9.40*	*8.93*
Carbohydrate			
Cereals	98	3.90	3.82
Legumes	97	4.20	4.07
Vegetables	95	4.20	3.99
Fruits	90	4.00	3.60
Sugars	98	3.95	3.87
Animal food	98	3.90	3.80
Overall average	*97*	*4.15*	*4.03*

Source: adapted from Merrill and Watt (1973).

and heat of combustion for lipids and carbohydrates. However, for proteins the net energy value is much lower than the coefficient of digestibility and heat of combustion (i.e., 4.05 vs. 5.20 kcal/g). This difference is explained by our earlier discussion that some of the energy stored in amino acids is lost due to the production of urea that incorporates the hydrogen bond.

Atwater general factors

Conveniently, the average net energy values may be rounded to simple whole numbers often referred to as Atwater general factors. These factors are illustrated as follows: 1 gram of carbohydrate = 4 kcal; 1 gram of lipid = 9 kcal; 1 gram of protein = 4 kcal. These values are named for Wibur Olin Atwater (1844–1907), an American chemist. They provide a viable and fairly accurate means of estimating the net energy consumption. They may be used to determine the caloric content of any portion of food or an entire meal from the food's composition and weight. As a result of the application of the Atwater general factors, virtually all food items on the market are currently labeled with an overall and nutrient-specific energy content. Table 8.2 illustrates how these factors are used for calculating the caloric values of chocolate-chip ice cream.

Bodily energy stores

Energy is stored in the body primarily as fat in the form of triglycerides, though a much smaller amount is also stored as glycogen in the muscle and liver. The body must have a steady supply of energy, and some of it comes from glucose, the simplest form of carbohydrate. As we eat, energy is supplied by the diet. Between meals, the breakdown of stored glycogen and fat helps in meeting energy needs. If no food is eaten for more than several hours, the body must shift the way it uses energy to ensure that glucose continues to be available. This is accomplished by increasing the use of stored fat and by mobilizing liver glycogen. The maintenance of blood glucose is of particular importance to the survival and functioning of the central nervous system. As shown in Table 8.3, glycogen stores are limited, and for an 80-kg person the body contains approximately 500 g of glycogen, which in theory could be depleted within several hours of strenuous exercise. Where glycogen stores decrease significantly, there will be an increase in protein degradation that produces amino acids. Some amino acids are converted into glucose, while others are directly metabolized for energy. Protein is not stored as an energy fuel in the body. It serves as a structural component of muscle tissue as well as many other organs. As such, a breakdown of protein for producing glucose and hence energy may result in the loss of muscle and other lean tissues.

Table 8.2 Method for calculating the caloric value of a food from its composition of macronutrients

Ice cream (100 g or 3.5 oz)	*Composition (%)*	*Weight (g)*	*Atwater Factors*	*Calories (kcal)*
Protein	3	3	4	12
Lipid	18	18	9	162
Carbohydrate	23	23	4	92
Water	56	56	0	0

Notes
Total calories: 266.
% kcal from lipids: 162/299 = 61%.
Calories = weight (g) × Atwater factors (Kcal/g).

Table 8.3 Availability of energy substrates in the human body

Substrates	*Weight (g)*	*Energy (kcal)*
Carbohydrate		
Muscle glycogen	400	1600
Liver glycogen	100	400
Plasma glucose	3	12
Total	503	2012
Lipids		
Adipose tissue	12,000	108,000
Intramuscular triglycerides	300	2700
Plasma triglycerides	4	36
Plasma fatty acids	0.4	3.6
Total	12,304	110,740

Source: adapted from McArdle *et al.* (2009); Vander *et al.* (2001).

Note
These values were estimated based on an average 80-kg man with 15% body fat.

Of the three energy-containing nutrients, the fat molecule carries the largest quantities of energy per unit weight. This occurs because of the greater quantity of hydrogen in the lipid molecule. In a well-nourished individual at rest, catabolism of lipids provides more than 50 percent of total energy requirements (Vander *et al.* 2001). Although most cells store small amounts of fat in their cytosol, most of the body's fat is stored in specialized cells known as adipocytes, which function to synthesize and store triglycerides during periods of food intake. As shown in Table 8.3, the potential energy stored in fat molecules for an 80-kg individual equals 110,700 kcal. Given an energy expenditure of 100 kcal per mile, this amount of energy can fuel an individual to run over 1100 miles. This contrasts sharply with the limited 2000 kcal of stored carbohydrate, which could only fuel a 20-mile run. During prolonged energy restriction, substantial amounts of fat are used to provide energy. However, when the supply of glucose is limited such as during starvation or under the diabetic state, fatty acids cannot be completely oxidized, and chemical ketones are produced. Ketones are the by-products produced mainly in the mitochondrial matrix of liver cells when carbohydrates are so scarce that energy must be obtained from breaking down fatty acids. Ketones may be used as an energy source by many tissues. In sustained starvation, even the brain adapts to meet some of its energy needs from utilizing ketones (Powers and Howley 2001).

Energy transformation

Energy transformation is the essence of life. It occurs in both living and non-living systems. As mentioned earlier, the energy transformation from one form to another follows the law of the conservation of energy. This law states that energy is neither created nor destroyed, but instead transforms from one state to another without being used up. For example, in photosynthesis, solar energy is harnessed by plants, which take carbon, hydrogen, oxygen, and nitrogen from their environment and manufacture carbohydrates, fats, or proteins. In the body, energy possessed by macronutrients is changed into chemical energy via cellular respiration, and is then stored within energy substrates or converted into mechanical and heat energy. The body stores energy in a variety of chemical compounds, including ATP, **phosphocreatine** (PCr), glycogen, and triglycerides. As an energy currency, ATP can be readily used to meet immediate energy

needs. However, this high-energy compound is stored in limited quantity. In fact, the body stores only 80 to 100 g of ATP at any one time (McArdle *et al.* 2005). This provides the energy that can only sustain maximal exercise for several seconds, such as a 60-yard sprint, high and long jump, base running, and football play. Consequently, in most sporting events and daily physical activities, ATP is always replenished continuously through a series of chemical reactions involving energy transformation. Three distinctive energy systems have been identified to play a role in replenishing ATP. They are: the ATP-PCr system, the glycolytic system, and the oxidative system.

The ATP-PCr system (phosphagen system)

The ATP-PCr system is also known as the **phosphagen system** because both ATP and PCr contain phosphates. This system serves as the immediate source of energy for regenerating ATP. This system is composed of three components. First, there is ATP itself. This high-energy compound, stored in the muscles, rapidly releases energy upon the arrival of electrical impulse. ATP is degraded to ADP by the enzyme ATPase. Because reaction involves combination with H2O, the splitting of ATP is often regarded as hydrolysis. This process may be illustrated as follows:

$$\text{ATP} \xrightarrow{\text{ATPase}} \text{ADP} + \text{Pi} + \text{Energy}$$

The second player of this system is PCr. This is another high-energy compound that exists in five to six times greater concentration in muscle than does ATP (Brooks *et al.* 2005). Unlike ATP, energy released by the breakdown of PCr is not used directly to accomplish cellular work. Instead, PCr provides a reserve of phosphate energy used to regenerate ATP as a result of muscle contraction and to prevent ATP depletion. In this process, ADP is combined with Pi to become ATP using the bonding energy stored in PCr. This reaction is catalyzed by the enzyme creatine kinase. This process may be illustrated as follows:

$$\text{PCr} + \text{ADP} \xrightarrow{\text{Creatine Kinase}} \text{ATP} + \text{Cr}$$

The third component of this system involves ADP and the action of the enzyme adenylate kinase or myokinase when referring to muscle. This enzyme's function is to catalyze the production of one ATP (and one AMP) from two ADPs. This process may be illustrated as follows:

$$\text{ADP} + \text{ADP} \xrightarrow{\text{Adenylate Kinase}} \text{ATP} + \text{AMP}$$

The three components of this immediate energy system and the respective kinase enzymes are all water soluble. As such, they exist throughout the aqueous part of the cell and in close proximity to the contractile elements of the muscle outside of the mitochondria. They can be immediately available to support muscle contraction. With some ATP being resynthesized from PCr, this system is able to fuel all-out exercises for approximately 5 to 10 seconds such as a 100-m sprint. It is frequently observed that during the last few seconds of the 100-m race, runners often slow down. If maximal effort continues beyond 10 seconds, or more moderate exercise continues for longer periods, ATP replenishment requires energy sources in addition to PCr.

The glycolytic system (glycolysis)

The **glycolytic system** uses only the energy stored in carbohydrate molecules such as glucose or glycogen for replenishing the ATP which the cell needs. This system is also

referred to as **glycolysis**, which contains a cascade of chemical reactions, each of which is catalyzed and regulated by a specific enzyme. As shown in Figure 8.3, glycolysis produces pyruvic acid. The production of pyruvic acid occurs regardless of whether oxygen is available. However, the availability of oxygen determines the fate of pyruvic acid. When oxygen is lacking, pyruvic acid is converted into lactic acid. Glycolysis is also referred to as the Meyerhof pathway in honor of Germen biochemist Otto Fritz Meyerhof (1884–1951) who was awarded the Nobel Prize in Medicine in 1922 for his discovery of such a pathway. Glycolysis may be summarized as follows:

$$\text{Glucose} \longrightarrow 2\,\text{ATP} + 2\,\text{Lactate-} + 2\,\text{H}^{+}$$

Glycolysis requires 12 enzymatic reactions for the breakdown of glycogen to lactic acid (1 for glycogen to become glucose, 10 for glucose to become pyruvic acid, and 1 for pyruvic acid to become lactic acid). This more complex chemical pathway involved makes this system relatively slower in generating ATP as compared to the ATP-PCr system. This energy-yielding pathway is similar to the ATP-PCr system in that both systems form ATP in the absence of oxygen and occurs in the watery medium of the cell outside the mitochondria.

This oxygen-independent system works predominantly within skeletal muscle tissue. This is especially the case in muscles consisting primarily of fast-twitch (i.e., Type IIb) muscle fibers. This type of muscle fiber contains a considerable amount of glycolytic enzymes. In muscle, glycogen is usually first broken down into glucose molecules via a process called **glycogenolysis**. These individual glucose molecules are then able to enter the glycolytic pathway. This pathway also allows the entry of glucose derived from liver glycogenolysis and transported via circulation. At the onset of glycolysis, ATP is used for glucose to be converted to glucose-6-phosphate, a compound necessary for this pathway to proceed. This is then followed by another energy-requiring reaction in which Fructose 6-phosphate is converted into Fructose 1,6-diphosphate. During the later reactions of glycolysis, the energy released from the glucose intermediates stimulates the direct transfer of a phosphate bond to ADP. This results in the production of up to four ATPs. Because two ATPs are lost in the initial steps of **phosphorylation** which uses ATP, for each glucose molecule entering the pathway this system generates a net gain of two ATPs. The process by which energy transfers from energy substrate to ADP via the phosphate bond that does not require oxygen is called substrate-level phosphorylation.

This system is relatively inefficient in terms of how much of the energy stored in a glucose molecule can result in ATP resynthesis. In fact, the amount of ATP produced from anaerobic glycolysis is only 5 percent of what a glucose molecule is capable of generating. In addition, this pathway is associated with the production of lactic acids, which may be involved in the onset of fatigue. This by-product of glycolysis can release hydrogen ions that increase acidity within the muscle cell, thereby disturbing the normal internal environment necessary for maintaining muscle contraction as well as other physiological functions. This system, however, has the advantage of replenishing ATP rapidly. With this system, most cells are able to withstand very short periods of low oxygen by using anaerobic glycolysis. Consequently, this energy system plays a major role in fueling sporting events in which energy production is near maximal for 30 to 120 seconds, such as a 400- and 800-meter run. There are special cases in which glycolysis supplies most, and in some cases all the ATP that a cell needs for surviving and functioning. For example, red blood cells contain the enzymes for glycolysis but have no mitochondria; all their ATP production occurs by glycolysis. In addition, as mentioned earlier, fast-twitch muscle fibers contain considerable amounts of glycolytic enzymes, but have few mitochondria. During intense exercise, these muscle fibers rely mainly on ATP derived from glycolysis.

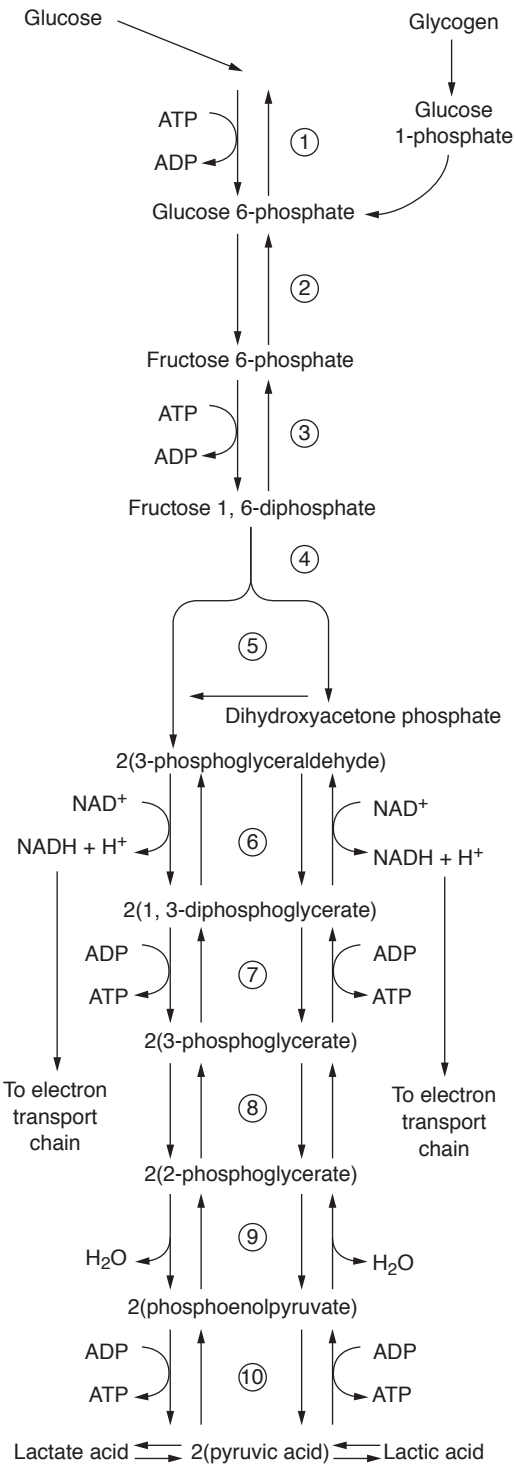


Figure 8.3 Glycolytic pathway in which glucose or glycogen is degraded into pyruvic acid

Source: Wilmore *et al.* (2008). Used with permission.

The oxidative pathway

Most of the energy used daily comes from the oxidation of carbohydrates, lipids, and, in rare cases, proteins consumed in the diet. Such aerobic production of energy occurs within mitochondria which are called "the powerhouses of the cell." Mitochondria are found scattered through the cytoplasm. As shown in Figure 8.4, mitochondria are oval-shaped bodies surrounded by two membranes and their internal space or matrix contains numerous enzymes that are capable of catalyzing oxidative energy transformation. As mentioned earlier, the glycolytic system captures only a very small portion of the energy stored in a glucose molecule. However, the oxidative system makes it possible for the remaining energy to be extracted from the glucose molecule. This is accomplished by converting pyruvate into **acetyl-CoA** rather than lactic acid, which is possible when oxygen is sufficient. Acetyl CoA can then enter the citric acid cycle, also known as the Krebs cycle.

The oxidative pathway involves three stages (Figure 8.5). Stage 1 is the generation of a key two-carbon molecule acetyl CoA. Note that acetyl CoA can be formed from the breakdown of carbohydrates, fats, or proteins. Stage 2 is the oxidation of acetyl-CoA in the Krebs cycle. In this process acetyl CoA combines with oxaloacetate to form citrate. What follow are a series of reactions to regenerate oxaloacetate and two molecules of CO_2, and the pathway begins again. The primary function of the Krebs cycle is to remove hydrogens and associated energy from various intermediates involved in the cycle using nicotinamide adenine dinucleotide (NAD) and flavin adenine dinucleotide (FAD) as hydrogen carriers. As a result, NADH and FADH are formed. The importance of hydrogen removal is that hydrogen atoms by virtue of the electrons they possess contain the potential energy stored in the food molecules. Both NADH and FADH then proceed through a series of oxidative reactions collectively called the electronic transport chain, stage 3 of the oxidative pathway. In this process, energy stored in these molecules is used to combine ADP and Pi to form ATP. Oxygen does not participate in the reactions of the Krebs cycle, but is the final hydrogen acceptor at the end of the electron transport chain that produces water. Because ATP is formed via the use of oxygen within mitochondria, this energy-yielding process is also termed **oxidative phosphorylation**. Using glucose as an example, this system may be summarized as follows:

$$C_6H_{12}O_6 + O_2 \longrightarrow 32\ ATP + 6CO_2 + 6H_2O$$

The oxidative system confers energy using oxygen, which differs from the ATP-PCr and anaerobic glycolysis systems. Due to its potential of extracting energy from all three

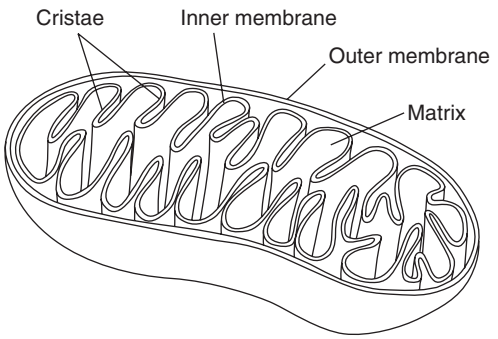


Figure 8.4 Structure of a mitochondrion

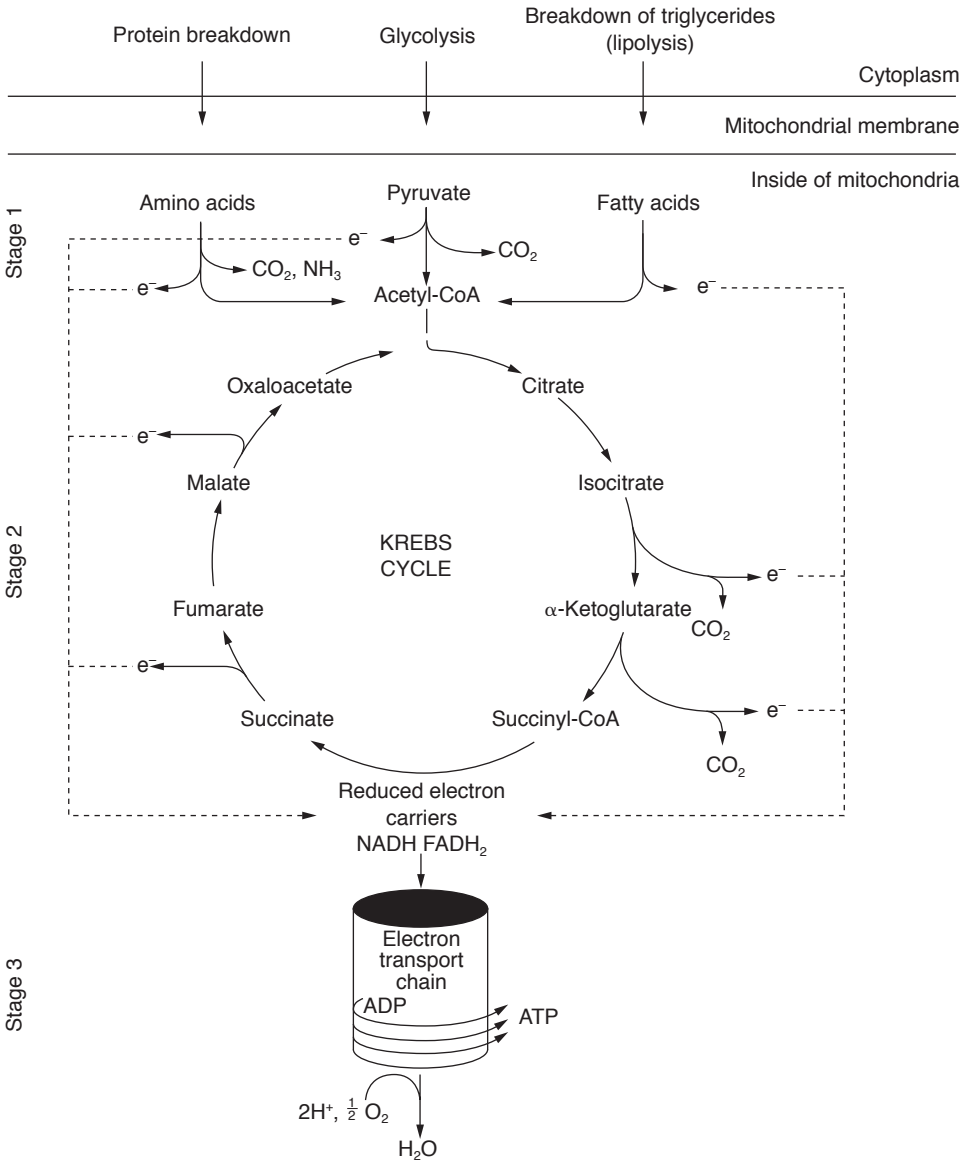


Figure 8.5 The three stages of the oxidative pathway of ATP production

Source: adapted from Mathews *et al.* (2000).

macronutrients, this system produces most of the energy throughout the day. The operation of both the Krebs cycle and the electron transport chain takes place in mitochondria. As such, the ability to generate energy aerobically depends in part on the size and content of mitochondria. Other factors such as myoglobin content and capillary density can also modulate the effectiveness of this system. This energy system is used primarily in sports-emphasizing endurance such as distance running ranging from 5 kilometers to the marathon and beyond.

Chemiosmotic hypothesis and uncoupling proteins

The mechanism as to how the oxidation of NADH and FADH is coupled to the phosphorylation of ADP may be further explained by the **chemiosmotic hypothesis** postulated by Peter Mitchell in 1961. He proposed that electron transport and ATP synthesis are coupled by a proton gradient across the inner mitochondrial membrane (Stryer 1988). In his model, the energy released as electrons is transferred along the respiratory chain leads to the pumping of protons H+ from the matrix to the other side of the inner mitochondrial membrane. As a result, there is a higher concentration of H^+ within the intermembrane space compared to that in the matrix. This then generates an electrical potential which serves as a source of energy to be captured. Mitchell proposed that it is this proton-motive force that drives the synthesis of ATP. Mitchell's hypothesis that oxidation and phosphorylation are coupled by a proton gradient has been validated by a wealth of evidence. In 1978, he was awarded the Nobel Prize in Chemistry due to his extraordinary contribution to our understanding of the fundamental mechanisms of bioenergetics.

According to the chemiosmotic theory as discussed above, cellular energy production takes place across the inner mitochondrial membrane. In this process, adenosine diphosphate (ADP) is phosphorylated to adenosine triphosphate (ATP) using energy associated with a gradient of protons that is generated during electron transport. If protons leak back into the matrix that abolishes the proton concentration gradient across the inner mitochondrial membrane, heat is produced instead of useful energy. This disruption of the connection between food breakdown and energy production is known as "uncoupling." It was long thought that energy metabolism was fully coupled to ATP production, which may then be stored or used in support of various cellular functions. However, with the discovery of **uncoupling proteins** (UCPs), it is now known that this notion is untrue. The proton gradient can be diminished by the action of UCP resulting in proton leak. In fact, in living cells a significant proportion of mitochondrial respiration is normally not coupled to the phosphorylation of ADP and energy that fails to be coupled to ATP synthesis is dissipated as heat.

UCPs play important roles in regulating energy balance. They can also decrease the production of reactive oxygen species (ROS) by mitochondria, which has been associated with the pathogenesis of obesity and/or type 2 diabetes. Energy expenditure in humans may be subdivided into: (1) basal energy expenditure or resting metabolic rate (RMR); (2) energy expenditure caused by physical activity; and (3) energy expenditure attributed to diet-induced thermogenesis. Uncoupling (proton leak) of mitochondria respiration to ATP synthesis constitutes a significant part of the RMR. UPC or proton leak has a marked influence on total energy expenditure and, in rats, accounts for approximately 20 to 30 percent of RMR (Rolfe and Brand 1996). It has also been estimated that in human, at least 20 percent of total energy expenditure is due to proton leaks, with the skeletal muscle as the main contributor (Lowell and Spiegelman 2000). Simply put, the more active the UPCs, the more the proton leak, and thus the greater the energy expenditure. To date, increasing energy expenditure by increasing proton leak in mitochondria has been recognized as an effective way to achieve weight loss.

Oxidation of lipids and proteins

Unlike the glycolytic pathway, which only applies to carbohydrates, the aerobic pathway allows oxidation of not only carbohydrates but also lipids and proteins, as shown in Figure 8.5. Lipids that normally participate in energy metabolism are triglycerides. Via **lipolysis**, triglycerides are hydrolyzed into fatty acids and glycerol (Figure 8.6). This reaction is catalyzed by enzyme lipase. Fatty acids can then undergo a series of reactions

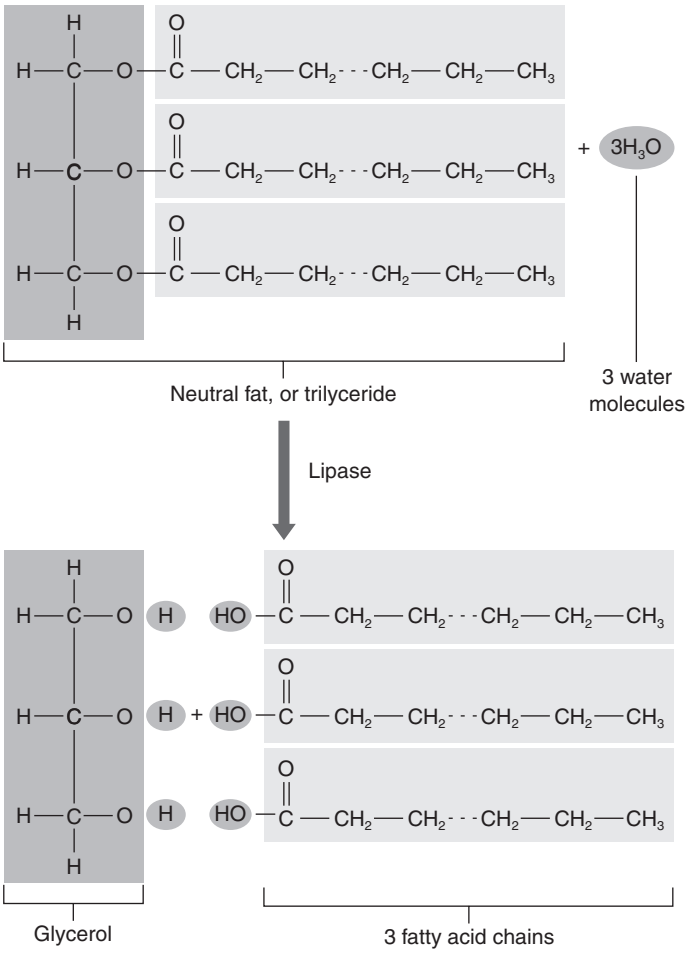


Figure 8.6 The schematic of reaction that a triglyceride molecule is hydrolyzed to free fatty acids and glycerol

to form acetyl-CoA. Although in the liver glycerol can be converted into an intermediate of glycolysis, which later becomes pyruvate and then acetyl-CoA, this does not occur to a great extent in skeletal muscle. Therefore, glycerol is not an important muscle fuel source during exercise (Gollnick 1985, Holloszy and Coyle 1984). Fat oxidation is a relatively slow process due to the complexity of its metabolism. Nevertheless, it has the ability to yield a large amount of energy. For example, oxidation of the fatty acid Palmitate, which contains 18 carbons, can liberate 129 ATP, nearly four times higher than the amount of ATP produced from oxidation of a glucose molecule.

Protein is not considered a major energy source, since it contributes less than 15 percent of the energy produced during exercise (Dolny and Lemon 1988, Gollnick 1985, Lemon and Mullin 1980). However, it can be crucial in maintaining energy continuity and glucose homeostasis under special circumstances such as starvation or prolonged strenuous exercise where bodily carbohydrate decreases significantly. Protein can enter bioenergetic pathways in many different places, but first needs to be cleaved into

amino acids. What happens next depends on which amino acids are involved. For example, some amino acids can be converted into glucose or pyruvate, some into acetyl-CoA, and still others to Krebs cycle intermediates. Before an amino acid can be used, the nitrogen residue must be removed. This is accomplished by switching the nitrogen to some other compound, a process known as transamination, or by removing nitrogen through oxidation, a process known as deamination. The energetic roles of carbohydrates, fats, and proteins during exercise are discussed in Chapter 9.

Energy transformation in sports and physical activity

ATP-PCr, glycolysis, and aerobic pathways are the three energy systems equipped by each individual. There are two inherent limits of the energetic processes: the maximal rate (power) and the amount of ATP that can be produced (capacity) (Sahlin *et al.* 1998). The power and the capacity vary drastically among the three energy systems, with both the ATP-PCr and glycolysis systems having a greater power but a lower capacity than the aerobic system. Brooks *et al.* (2005) have attempted to classify athletic activities into one of the three groups: power, speed, and endurance. Such a classification has an advantage of allowing us to identify a predominant energy system for many different athletic activities. This will then lead to a proper design of training aimed to enhance the performance of such energy system. According to this classification, intra-muscular high-energy phosphate compounds ATP and PCr supply most of the energy for power events such as short-distance sprinting and weight lifting. For rapid, forceful exercises that last about a minute or so, muscle depends mainly on glycolytic energy sources. Intense exercise of longer duration (i.e., >2 minutes) such as middle-distance running and swimming requires a greater demand for aerobic energy transfer. Table 8.4 illustrates energy sources of muscular work for various types of athletic activities.

It should be noted that activities listed in Table 8.4 are primarily track and swimming events in which exercise lasts continuously for a given time period. The fact that these individual events differ only in duration has enabled us to estimate energy expenditure and fuel utilization using laboratory instrumentations. It is difficult to draw a general

Table 8.4 Energy source of muscular work for different types of sporting events

	Power	*Speed*	*Endurance*
Event	Shot put Discus Weight-lifting High jump 40 yard dash Vertical jump 100 m sprint	200–800 m run 100–200 m swim	1500 m run 10 km run 400–800 m swim Cross-country Road cycling Marathon
Duration of event	0–10 seconds	10 seconds–2 minutes	>2 minutes
Major sources of energy	ATP PCr	ATP PCr Muscle glycogen	Muscle glycogen Liver glycogen lipids
Energy system involved	ATP-PCr	Glycolysis	Aerobic pathway
Rate of process	Very rapid	Rapid	Slower
Oxygen required	No	No	Yes

Source: adapted from Brooks *et al.* (2005).

conclusion on energy metabolism in team sports such as soccer, field hockey, and lacrosse. This is because energy and fuel requirements for performing these stop-and-go sports may vary depending on field position and duration of each burst of exercise. Using soccer as an example, it is likely that those who play midfield positions run longer and therefore derive proportionally more of their total energy from aerobic sources. Conversely, those who play forward positions often sprint and thus use a majority of the total energy coming from the ATP-PCr system.

The three energy systems may also be classified according to whether the operation of the system requires a proper supply of oxygen. In this context, both the ATP-PCr and glycolysis systems are regarded as anaerobic in that they operate outside of mitochondria and energy transferring does not require oxygen. On the other hand, the oxidative system utilizes oxygen as the electron acceptor so that energy transfer can proceed. Most sporting events or physical activities are often categorized as to whether they are anaerobic or aerobic. This classification has made it easier to convey to the public whether the activity is tolerable. Generally, activities that demand primarily aerobic sources of energy are less intense but more enduring such as walking, jogging, cycling, and swimming. Conversely, activities that require anaerobic sources of energy are generally intense, fast moving, and more explosive such as sprinting and jumping. They can also be resistance exercises in which muscle tension increases significantly once contracted.

How the three energy systems respond during exercise of changing intensity is a complex issue. This is because as exercise intensity increases, a transition from one energy system to another will occur. It must be kept in mind that for most activities energy needed is not provided by simply turning on a single energetic pathway, but rather a mixture of several energy systems operating in a sequential fashion but with considerable overlap. Such a mixed use of energy systems may be particularly manifested during (1) rest-to-exercise transition, and (2) during incremental exercise in which intensity rises progressively. In the transition from rest to light or moderate exercise, oxygen consumption increases progressively to reach a steady state within one to four minutes. The fact that oxygen consumption does not increase instantly to the desirable level suggests that energy systems other than oxidative pathways contribute to the overall production of ATP at the beginning of exercise. There is evidence to suggest that at the onset of exercise the ATP-PCr system is the first bioenergetic pathway being activated, followed by glycolysis, and finally aerobic energy production. However, once a steady state is reached, the body's ATP requirement can be met primarily via aerobic metabolism.

Control of energy transformation

It must be kept in mind that the increased rate of energy metabolism does not always occur and happens only if there is an increase in energy demand. In this context, questions remain as to how such demand-driven energy metabolism comes about and how the body modulates the rate of energy metabolism. Muscular exercise may be considered a dramatic test of the body's homeostatic control systems. This is because exercise has the potential to disturb many homeostatic variables. For example, heavy exercise results in high increases in muscle oxygen (O_2) requirements, and large amounts of carbon dioxide (CO_2) being produced. These changes must be corrected by increases in breathing and blood flow to increase (O_2) delivery to the exercising muscle and remove metabolically produced CO_2, which will otherwise increase the body's acidity. In addition, as heavy exercise begins, there is an immediate increase in the use of ATP. As a result, ATP storage decreases. The body's energy systems must respond rapidly to replenish ATP from substrates such as PCr and carbohydrates so that a continuous energy supply and thus energy homeostasis can be maintained.

Homeostasis and steady state

French physiologist Claude Bernard was the first to recognize the central importance of maintaining a stable internal environment in 1857. This concept was further elaborated and supported in 1932 by the American physiologist Walter Cannon, who emphasized that such stability could be achieved only through the operation of a carefully coordinated physiological process. The activities of cells, tissues, and organs must be regulated and integrated with each other in such a way that any change in the internal environment initiates a reaction to minimize the change. As such, Cannon described the term **homeostasis** as the maintenance of a constant or unchanging internal environment. It must be noted that changes in the composition of the internal environment do occur, but the magnitude of these changes is small and kept within narrow limits via multiple coordinated homeostatic processes.

A similar term, **steady state**, is often used by exercise scientists to denote a steady physiological environment. Although the terms steady state and homeostasis are often used interchangeably and both result from compensatory regulatory responses, homeostasis generally refers to a relatively constant environment during un-stressful conditions such as rest, whereas a steady state does not necessarily mean that the internal environment is completely normal, but simply that it is unchanging (Vander *et al.* 2001). In other words, a steady state only reflects a stability of the internal environment that is achieved by balancing the demands placed on the body and the body's responses to those demands. An example which helps in distinguishing these two terms is the case of oxygen consumption during exercise. As shown in Figure 8.7, upon the commencement of moderate intensity exercise, oxygen uptake reaches a plateau within a few minutes. This plateau of oxygen uptake represents a steady-state metabolic rate specific to the exercise. However, this constant oxygen uptake occurs at the rate that is greater than the resting level of metabolism, and thus does not reflect a true homeostatic condition.

The fact that the internal environment, such as body temperature, blood pressure, plasma glucose or acidity, is always maintained relatively constantly in most circumstances suggests that the body operates many control systems that work to maintain homeostasis on a regular basis. Indeed, every one of the fundamental processes performed by any single cell must be carefully regulated. What determines how much glucose enters a cell? Once inside the cell, what determines how much of this glucose is used for energy and how much is stored as glycogen? To answer these questions, it is important for us to understand not only the metabolic processes, but also the mechanisms which control them.

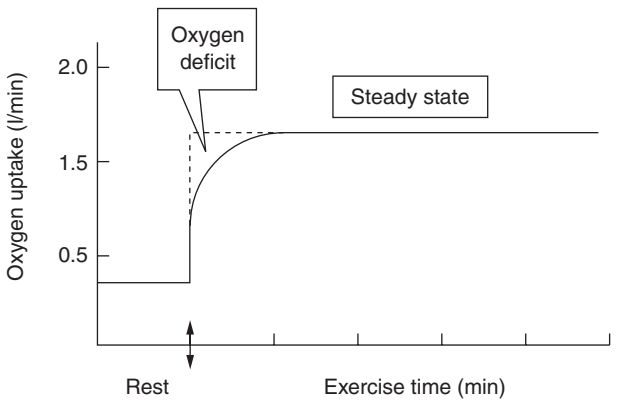


Figure 8.7 The time course of oxygen uptake (VO_2) in the transition from rest to submaximal exercise

The control system and its operation

The body has hundreds of different control systems that regulate certain physiological variables at or near a constant value. A control system within the organism may be defined as a series of interconnected components that maintain physiological and chemical parameters of the body at near constant value. The general components of the system are (1) receptors, (2) afferent pathways, (3) integrating centers, (4) efferent pathways, and (5) effectors. Figure 8.8 represents the schematic of such a control system. A receptor is capable of detecting the unwanted change or disturbance in the environment and sends the message to the integrating center that assesses the strength of the stimulus and the amount of response needed to correct the disturbance. The pathway traveled by the signal between the receptor and the integrating center is known as the afferent pathway. The integrating center then sends an appropriate output message to an effector, which is responsible for correcting the disturbance and causes the stimulus to be removed. The pathway along which this output message travels is known as the efferent pathway.

Most control systems of the body operate via **negative feedback**. Negative feedback is defined as the working process in which a change in the variable being regulated brings about responses that tend to push the variable in the direction opposite to the original change. An example of negative feedback may be seen in the respiratory control of CO_2 concentration in the extracellular fluid. In this case, an increase in extracellular CO_2 above the normal level triggers a chemical receptor, which sends information to the respiratory control center in the brainstem to increase breathing. Effectors in this example are respiratory muscles and an increase in their contraction will reduce extracellular CO_2 concentration back to normal, thereby re-establishing homeostasis. There is, however, another type of feedback known as positive feedback in which an initial disturbance in a system sets off a series of events that increases the disturbance event further. Apparently, the positive feedback does not favor the maintenance of the internal environment.

Traditionally, the concept of the control system was restricted to situations in which the first four of the components are all parts of the nervous system. However, currently, this term is no longer so narrowly focused and recognizes that the principles are

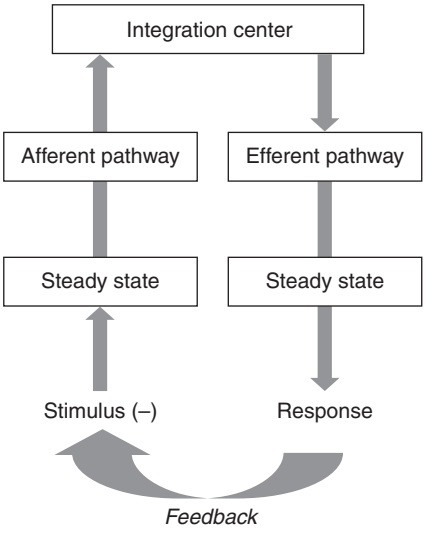


Figure 8.8 Schematic illustration of a biological control system

essentially the same when blood-borne messengers such as hormones, rather than nerve fiber, serve as the afferent or, much more commonly, the efferent pathway, when an endocrine gland serves as the integrating center. For example, in the case of thermoregulation when the body temperature drops, the integrating centers in the brain not only send signals by way of nerve fibers to muscles to trigger contraction, but also cause the release of hormones that travel by the blood to many target cells producing an increase in thermogenesis. Although hormones play an integral role in maintaining homeostasis, a control system that involves hormones could lack a receptor and an afferent pathway. For example, the release of parathyroid hormone is triggered by a fall in plasma calcium concentration. This hormone then functions to increase a release of calcium from bone into the blood. Likewise, the release of insulin is caused by a rise in plasma glucose concentration. This hormone then functions to increase cellular glucose uptake from the blood. In both examples, the objective of the control system involved is to maintain a normal plasma concentration of calcium or glucose. However, neither control process involves a receptor or an afferent pathway. This is because glandular cells themselves are sensitive to the change in chemical concentration of the blood supply to them (Vander *et al.* 2001).

Neural and hormonal control systems

In light of the previous discussion, it is clear that both the nervous and endocrine systems are involved in the control and regulation of various functions in order to maintain homeostasis. Both are structured to be able to sense information, organize an appropriate response, and deliver the message to the proper organ or tissue. The two systems often work together to maintain homeostasis. However, they differ in that in order to deliver the output message the endocrine system relies on hormonal release, whereas the nervous system uses **neurotransmitters**, which are referred to as endogenous chemicals that transmit signals from a neuron to a target cell across a synapse.

With regard to the nervous control, the autonomic nervous system is the efferent branch of the nervous system and is most directly related to the regulation of the internal environment (Brooks *et al.* 2005). The autonomic nerves innervate glands, blood vessels, cardiac muscle, and smooth muscle found in the respiratory and gastrointestinal systems. As such, the system operates below the conscious level. The autonomic nervous system may be further divided into **sympathetic** and **parasympathetic** divisions. The parasympathetic division controls resting functions and has effects such as slowing the heart rate and stimulating digestion. It comprises neurons that release **acetylcholine** (ACh). On the other hand, the sympathetic division controls fight-or-flight responses. Unlike the parasympathetic division, this division comprises two types of neurons. The first neuron releases ACh, but the second neuron that directly innervates the cell releases **norepinephrine**. These neurotransmitters bind to the receptors in the cell membranes of target tissues, altering the membrane permeability to certain ions. For example, in the heart, ACh promotes the entry of Cl^{-1} to deter the occurrence of action potential, whereas norepinephrine stimulates entries of Na^{+} and Ca^{++} to facilitate the production of action potential. Consequently, ACh slows heart rate, whereas norepinephrine speeds up heart rate.

The endocrine glands release hormones directly into the blood, which carries the hormone to a tissue to exert an effect. The hormone exerts its effect by binding to a specific protein receptor. In doing so, the hormone can circulate to all tissues, but will only affect the tissues that have the specific receptor. As mentioned earlier, hormonal secretion from the endocrine glands is regulated by feedback mechanisms. That is to say that a hormone is released in response to a change in the internal environment. However,

the secretion of the hormone will diminish and eventually stop if a particular end result of the hormonal action is achieved. Of the many endocrine glands, both the pancreas and adrenal glands are perhaps most relevant to exercise metabolism.

The pancreatic hormones are proteins secreted by the islets of Langerhans, clusters of endocrine cells in the pancreas. Islets of Langerhans contain several distinct types of cells of which both α and β cells have been thoroughly investigated. The β cells secrete insulin which stimulates glucose and amino acid uptake by many cells of which muscle and adipose tissue are quantitatively the most important. This will then be followed by increased synthesis of glycogen and protein in muscle and triglycerides in adipose tissue (Table 8.5). High levels of circulating insulin also inhibit hepatic glucose output and thus promote glycogen as well as triglyceride synthesis in the liver. The α cells of the pancreas secrete glucagon. While insulin promotes removal of glucose from the blood if it is too high, glucagon functions to raise blood glucose level if it is too low. Unlike insulin, glucagon exerts its effect primarily on the liver. It enhances both glycogenolysis and gluconeogenesis, the two processes that generate free glucose (Table 8.5). An increase in gluconeogenesis is achieved via glucagon's role of stimulating hepatic amino acid uptake. Both insulin and glucagon function together to help maintain a relatively stable blood glucose concentration.

The adrenal gland contains two sections: the adrenal medulla and the adrenal cortex. The adrenal medulla releases both epinephrine and norepinephrine, which are collectively called catecholamines. These two hormones are not only involved in activating energy metabolism in order to meet the demand of exercise, but also in maintaining blood glucose concentration (Table 8.5). They are also important in regulating cardiovascular and respiratory responses in an effort to facilitate energy homeostasis. The adrenal medulla is innervated by the sympathetic nervous system. As such, sympathetic activity stimulates the secretion of these hormones from the adrenal medulla. The adrenal cortex, the outer part of the adrenal gland, produces cortisol, aldosterone, and sex hormones, of which only cortisol is directly related to energy metabolism. Cortisol contributes to the maintenance of plasma glucose by stimulating lipolysis in adipose tissue and gluconeogenesis in the liver (Table 8.5). Unlike catecholamines whose release is controlled by sympathetic nerves, cortisol secretion is subject to the action of the stimulating hormones secreted by the hypothalamus and is regulated by a negative feedback mechanism.

In order to produce their action, catecholamines interact with two receptors, referred as α and β receptors, located on the cell membrane surface. Norepinephrine mainly affects the α receptors, whereas epinephrine affects both α and β receptors. The β receptors may be further subdivided into β1 and β2 receptors. In general, the β1 receptors influence cardiac function, while β2 is related to tissue metabolism. The actions of these receptors are listed in Table 8.6. Both α and β receptors are also called adrenergic in that they can be activated by epinephrine and norepinephrine. These receptors once bound to either hormone will cause changes in cellular activity by increasing or decreasing the cyclic AMP or Ca^{2+}, which are often referred to as **second messengers**. Second messengers are intracellular molecules or ions that are regulated by extracellular signaling agents such as neurotransmitters and hormones (first messengers). The second messenger then activates another set of enzymes called protein kinases, which trigger various cellular events in response to the original stimulus. Unlike catecholamines which comprise peptides, cortisol is a lipid hormone and can diffuse easily through the cell membrane and become bound to a protein receptor in the cytoplasm of the cell. The hormone-receptor complex enters the nucleus and binds to a specific protein linked to DNA. This then leads to the synthesis of proteins necessary to alter the metabolism. This process does not involve the production of second messengers. It takes longer for the action of cortisol to be turned on, but its effect will last longer as compared to catecholamines.

Table 8.5 Selected hormones and their catabolic role in maintaining energy homeostasis

Endocrine gland	*Hormone*	*Catabolic action*	*Controlling mechanism*	*Stimuli*
Anterior pituitary gland	Growth hormone	• Mobilization of FFA • Gluconeogenesis	• Hypothalamic GH-releasing hormone	• Exercise stress • Low plasma glucose
Pancreatic β cells	Insulin	• Uptake of glucose, amino acids, and FFA into tissue	• Plasma glucose concentration • Autonomic nervous system	• Elevated plasma glucose • Decreased epinephrine and norepinephrine
Pancreatic α-cells	Glucagon	• Mobilization of FFA and glucose • Gluconeogenesis	• Plasma glucose concentration • Autonomic nervous system	• Low plasma glucose • Elevated epinephrine and norepinephrine
Adrenal cortex	Cortisol	• Mobilization of FFA gluconeogenesis	• Hypothalamic adrenal cortex stimulating hormone	• Exercise stress • Low plasma glucose
Adrenal medulla	Epinephrine nor-epinephrine	• Glycogenolysis mobilization of FFA	• Autonomic nervous system	• Exercise stress • Low plasma glucose

Table 8.6 Interaction of epinephrine and norepinephrine with adrenergic receptors

Receptor type	*Intracellular mediator*	*Effect*
α	Cyclic AMP and Ca^{++}	• Vasoconstriction • Gastrointestinal relaxation
$\beta 1$	Cyclic AMP	• Increased heart rate • Increased cardiac contraction • Increased lipolysis • Increased glycogenolysis
$\beta 2$	Cyclic AMP	• Vasodilation • Bronchodilation

Source: adapted from Tepperman and Tepperman (1987).

Summary

- Energy is defined as the ability to perform work. It is neither created nor destroyed, but instead transforms from one state to another without being used up. The two major interchangeable forms of energy as related to human movement are kinetic and potential energy.
- ATP serves as the body's energy currency, although its quantity is very limited. The free energy yielded from splitting of the phosphate bond of ATP powers all forms of biological work. In most activities, ATP is generated instantly from the degradation of carbohydrates and fats.
- Carbohydrates, fats, and proteins represent the three energy-containing nutrients consumed daily. As compared to fat, carbohydrate stored as glycogen is relatively limited. However, it is a preferable source of energy. Protein contains energy, but contributes little to energy metabolism. Carbohydrate and protein each provide about 4 kcal of energy per gram, compared with about 9 kcal/gram for fat.
- The potential energy stored in nutrients is captured through three energy yielding systems: (1) the ATP-PCr system, (2) the glycolytic system, and (3) the oxidative system. The operation of these systems is of essence to the continual supply of ATP in support of various biological functions.
- The three energy systems differ considerably in terms of rate and capacity of producing ATP, and their contribution will vary depending on the intensity and duration of an activity. However, such differences among the three energy systems provide the ability for the body to be able to derive energy under various circumstances whether generating explosive power, enduring a long-distance event, or simply performing a household activity. The oxidative system involves a breakdown of fuels with the use of oxygen. Compared with the ATP-PCr and glycolytic systems, operation of the oxidative system is slowest in generating ATP. However, it is most capable of extracting energy stored in energy-containing nutrients. The oxidative system also represents a "common" pathway shared by carbohydrates, fats, and proteins for being used as an energy source.
- UCPs play important roles in regulating energy balance. They function to disrupt or uncouple food breakdown and ATP production, thereby increasing fuel utilization and energy expenditure. Activities of UCPs account for approximately 20 to 30 percent of resting metabolic rate. The more active the UPCs, the greater the energy expenditure.
- For most activities, energy needed is not provided by simply turning on a single energetic pathway, but rather by a mixture of several energy systems operating

currently. However, the percentage of contribution of each system differs depending on the intensity and duration of the activity.

- The term homeostasis is defined as the maintenance of a constant internal environment. It differs from the term steady state in that the latter represents a constant internal environment achieved under stressful conditions such as exercise.
- The maintenance of a constant internal environment is achieved by many biological control systems that operate mainly in a negative feedback manner and are capable of detecting, processing, and making appropriate adjustments to correct the changes.
- Both the nervous and endocrine systems often work together as part of a control system. They are structured so as to be able to sense information, organize an appropriate response, and deliver the message via neurotransmitters or hormones to the proper organ or tissue in order to exert their actions.
- Hormones involved in energy metabolism exert their effect by first combining with protein receptors and then activating enzymes necessary to catalyze intended chemical reactions. Specifically, for those peptide hormones such as catecholamines, binding with receptors takes place on the cell membrane, which triggers the production of a second messenger needed to carry out hormonal actions within the cell. This process differs from lipid-like hormones such as cortisol, which always diffuses across cell membrane and binds to a receptor within the cell before exerting its action.

Case study: do energy drinks really provide a source of energy?

Rhonda had just landed the job of her dreams as a writer for *Runners' World* magazine. Since high school, where she had excelled in cross-country events, Rhonda had been a consistent runner. Her first assignment was to write a report on the efficacy of an energy drink called XS Citrus Blast®. It was required that to write this report she had to be very accurate in her analysis. Rhonda knew that XS Citrus Blast® had been used by athletes to provide some "fuel" as they practiced and competed. She also saw other people using it more casually as a way to become "energized." However, she was confused about the labeling of the drink. For example, XS Citrus Blast® boasted that it contained no calories but still provided energy. That made no sense based on what Rhonda knew about biological energy! Rhonda decided to find out more details about this drink before she began to write. The following facts are what she discovered:

- Ingredients: carbonated water, taurine, glutamine, citric acid, adaptogen blend, natural flavors, acesulfame potassium, caffeine, sodium benzoate, potassium sorbate, sucralose, niacin, pantothenic acid, pyridoxine HCL, yellow 5, cyanocobalamin.
- Nutrition facts: serving size: 8.4 fl oz; servings per container: 1; calories: 8; fat: 0 g; sodium: 24 mg; potassium: 25 mg; total carbs: 0 g; sugars: 0 g; protein: 2 g; vitamin B3: 100%; vitamin B6: 300%; vitamin B5: 100%; vitamin B12: 4900%.

Questions

- What is a biological definition of energy?
- When we say that something gives us "energy," what does that mean?
- Why is the XS Citrus Blast® that contains only 8 calories considered an "energy booster"?
- What ingredients and nutrients provide energy? How do they do that?

Review questions

1 Define the term energy. What is the law of the conservation of energy?
2 Define the terms (1) bioenergetics, (2) mitochondria, (3) catabolism, and (4) anabolism.
3 Define kinetic and potential energy. Provide examples that illustrate the transformation between these two forms of energy.
4 What does the "coefficient of digestibility" mean? Why does protein have the lowest coefficient of digestibility?
5 How much glycogen does an 80-kg person possess? How is glycogen distributed between the muscle and the liver?
6 What is a bomb calorimeter and how does it work?
7 What are Atwater general factors?
8 What is the total energy stored in food containing 50 g of carbohydrate, 15 g of fat, and 8 g of protein?
9 Compare the three energy systems (e.g., phosphagen system, glycolytic system, and oxidative system) in terms of complexity, cellular location, end products, oxygen requirements, and rate and capacity of ATP production.
10 Name some sport events and physical activities that are mainly supported by each of the three energy systems.
11 Define the terms (1) glycerol, (2) pyruvate, (3) acetyl CoA, (4) NADH, and (5) FADH.
12 Creatine monohydrate, sodium bicarbonate, phosphate, vitamins B2 and B3, and Co-Q_{10} are the supplements discussed in the context of bioenergetics. Please match each of these supplements with a specific energy system and explain specifically how each works.
13 State the chemiosmotic hypothesis and discuss its potential application.
14 Define the term homeostasis. How does it differ from the term steady state?
15 What are the components of a biological control system? List an example that illustrates the operation of a control system.
16 Describe how each of the following hormones affect carbohydrate, fat, and protein utilization during exercise: (1) growth hormone, (2) insulin, (3) glucagon, (4) cortisol, (5) epinephrine, and (6) norepinephrine.

Suggested reading

1 Burke LM (2001) Energy needs of athletes. *Canadian Journal of Applied Physiology*, 26(Suppl): S202–S219.
This article provides practical advice about how athletes should use their energy budget to choose foods that provide macronutrient and micronutrient needs for optimal health and performance.
2 Fitts RH (1996) Muscle fatigue: the cellular aspects. *American Journal of Sports Medicine*, 24(6 Suppl): S9–S13.
This article addresses exercise-induced cellular changes that may lead to muscle fatigue and how diet and fluid replacement may help counteract such changes and thus prevent or delay fatigue.
3 Gastin PB (2001) Energy system interaction and relative contribution during maximal exercise. *Sports Medicine*, 31: 725–741.
The author provides a more contemporary overview of how the three distinctive energy systems operate during exercise. Some of the misconceptions with regard to how these energy systems are affected by exercise intensity and duration are also discussed.

Glossary

Acetylcholine neurotransmitters released by neurons of parasympathetic division of the autonomic nervous system.

Acetyl-CoA a molecule that functions to convey the carbon atoms to the Krebs cycle to be oxidized for energy production.

Adenosine triphosphate high-energy compound used for a variety of biological work, including muscle contraction, synthesizing molecules, and transporting substances.

Bioenergetics a field of biochemistry that concerns chemical pathways responsible for converting energy-containing nutrients into a biologically usable form of energy.

Biosynthesis a process in which energy in one substance is transferred into other substances so that their potential energy increases.

Catabolism a process in which more complex substances are broken down into simpler ones.

Chemiosmotic hypothesis this hypothesis states that electron transport and ATP synthesis are coupled by a proton gradient across the inner mitochondrial membrane.

Digestive efficiency referred to as the coefficient of digestibility that represents the percentage of ingested food digested and absorbed to serve the body's metabolic needs.

Energy the ability to produce change and measured by the amount of work performed during a given change.

First law of thermodynamics the law states that the body does not produce, consume, or use up energy; it merely transforms energy from one state to another.

Flavin adenine dinucleotide a coenzyme found in all living cells that functions as a hydrogen carrier.

Glycogenolysis a process in which glycogen is broken down into glucose molecules.

Glycolysis the same as the "glycolytic system."

Glycolytic system also referred to as glycoylsis which uses only the energy stored in carbohydrate molecules for regenerating ATP.

Homeostasis the maintenance of a constant or unchanging internal environment.

Kinetic energy the energy possessed by an object due to its motion.

Lipolysis a process in which triglycerides are broken down into fatty acids and glycerol.

Mechanical energy a form of energy possessed by an object due to its motion or its position or internal structure.

Negative feedback the working process in which a change in the variable being regulated brings about responses which tend to push the variable in the direction opposite to the original change.

Neurotransmitters endogenous chemicals that transmit signals from a neuron to a target cell across a synapse.

Nicotinamide adenine dinucleotide a coenzyme found in all living cells that functions as a hydrogen carrier.

Norepinephrine neurotransmitters released by neurons of sympathetic division of the autonomic nervous system.

Oxidation any chemical reaction that involves a loss of electrons.

Oxidative phosphorylation a metabolic pathway that uses energy released by the oxidation of nutrients to produce ATP.

Oxidizing agents the substance that gains electrons as it reduces.

Parasympathetic a branch of the autonomic nervous system that slows the heart rate and stimulates digestion.

Phosphagen system also referred to as the ATP-PCr system which serves as the immediate source of energy for regenerating ATP.

Phosphocreatine a phosphorylated creatine molecule which serves as a rapidly mobilizable reserve of high-energy compounds.

Phosphorylation a process in which energy transfers from energy substrate to ADP via phosphate.

Potential energy the energy possessed by an object due to its position or internal structure.

Redox a process in which oxidation and reduction reactions are coupled.

Reducing agents the substance that donates or loses electrons as it oxidizes.

Reduction any chemical reaction that involves a gain in electrons.

Respiratory chain the transport of electrons by specific carrier molecules that represents the final pathway of aerobic metabolism.

Second messengers intracellular molecules or ions that are regulated by neurotransmitters or hormones and function to activate another set of enzymes.

Steady state a steady physiological environment in which energy demand is met by energy supply.

Sympathetic a branch of the autonomic nervous system that promotes fight-or-flight responses, including increases in heart rate and breathing rate and decreases in digestion.

Uncoupling proteins mitochondrial inner membrane proteins which function to disrupt the connection between food breakdown and energy production.

9 Nutrients metabolism

Contents

Key terms

- *β*–oxidation
- Branched-chain amino acids
- Carnitine palmitoyl transferase (CPT)
- Amino acid pool
- Carnitine
- Delayed onset of muscle soreness (DOMS)

- Endogenous
- Fatmax
- Glycogen phosphorylase
- Hyperglycemia
- Insulin-like growth factors
- Lactate threshold
- Malonyl CoA
- Phosphofructokinase
- Somatomedins
- Translation
- Epinephrine
- Gluconeogenesis
- Hepatic glucose output
- Hypoglycemia
- Isocitrate dehydrogenase
- Lipase
- Nitrogen balance
- Pyruvate dehydrogenase
- Transcription

Carbohydrate metabolism

Exercise poses a serious of challenge to the bioenergetic pathways in the exercising muscle. For example, during heavy exercise, the body's total energy output may increase 15 to 20 times above that of the resting condition. Most of this increase in energy production is used to provide ATP for contacting skeletal muscles, which may increase their energy utilization 200 times over utilization at rest. Therefore, it is apparent that skeletal muscles have a great capacity to produce and use large quantities of ATP during exercise. Such a large increase in ATP production is made possible by our ability to extract the energy stored in carbohydrates, lipids, and proteins we consume daily. In this context, a strong tie exists between nutrition and sports performance. Compared to lipids and proteins, carbohydrate remains the preferential fuel during high-intensity exercise because it can rapidly supply ATP both aerobically and anaerobically. Therefore, emphasizing a sufficient consumption of carbohydrates daily should be an integral part of a training regimen for most athletes. Lipids represent another potential source of energy. However, their catabolism normally results in a lower energy turnover that cannot quite match the energy demand imposed by most sporting events. Given that excess lipids can have a negative impact upon one's health, it is equally important to understand the unique characteristics associated with lipid metabolism, so that an effective lifestyle strategy may be developed to facilitate fat loss.

Carbohydrate: a limited but ideal energy source during exercise

Two main macronutrients provide energy for replenishing ATP during exercise: (1) muscle and liver glycogen; (2) triglycerides within adipose tissue and exercising muscle. To a much less degree, protein or amino acids within skeletal muscle can donate carbon skeletons thereby furnishing energy. During prolonged exercise, carbohydrates such as muscle glycogen and blood glucose derived from liver glycogenolysis are the primary energy substrates. Glycogen is a readily mobilized storage form of glucose. It is a very large branched polymer of glucose residues, as mentioned in Chapter 2 (Figure 2.4). Glycogen undergoes a process of glycogenolysis that yields free glucose molecules. This glucose can then enter the glycolytic pathway in which energy is transformed.

It must be emphasized that the body stores a limited amount of carbohydrates. As discussed in Chapter 8, energy stored in muscle and liver glycogen is only about 2000 kcal which is only 2 percent of that stored in triglycerides (i.e., 110,000 kcal) (Table 8.3). In addition, some important organs can, under normal circumstances, only use carbohydrate as a fuel source to survive and function. The brain is the best example. The adult brain requires about 100 g glucose per day, close to the amount of glycogen stored in the liver. In fact, one of the important roles liver glycogen plays is to maintain an adequate blood glucose concentration so that the brain can function properly. Glycogen

stored in skeletal muscles, on the other hand, serves as a fuel source mainly for the muscles themselves.

The importance of their availability during exercise is demonstrated by the observation that fatigue is often associated with muscle glycogen depletion and/or hypoglycemia. With respect to energy provision, carbohydrates are superior to fat in that (1) they may be used for energy with and without oxygen; (2) they provide energy more rapidly; (3) they must be present in order to use fat; (4) they are the sole source of energy for the central nervous system, and (5) they can generate 6 percent more energy per unit of oxygen consumed.

Carbohydrate utilization at onset of exercise

As mentioned in Chapter 8, phosphocreatine or PCr is the primary energy substrate available for replenishing ATP during very intense muscular exercise of short duration (i.e., ≤10 s). This idea was initially supported both by theoretical calculations of the energy required for the production of muscle force and the rapid decline in PCr found during very intense exercise. Consequently, it has long been assumed that the provision of energy via a particular metabolic pathway is linked sequentially; that is, during intense exercise, PCr stores are almost depleted in the initial 10 s and further contractile activity is then sustained by the metabolism of muscle glycogen. However, it is now understood that carbohydrate, particularly glycogen and glucose, will take a fair share of energy provision at the onset of exercise. Boobis *et al.* (1982) found that with all-out bicycle ergometer exercise aimed to accomplish as much work as possible in 6 s, a 35 percent decrease in PCr occurred along with a 15 percent reduction in glycogen. When such exercise was performed for 30 s, a 65 percent decrement in PCr was found concomitant with a 25 percent reduction in glycogen. Similar results have been reported for short duration maximal treadmill running and cycling (Cheetham *et al.* 1986, McCartney *et al.* 1986). Collectively, these studies indicate that PCr breakdown and glycogenolysis occur concomitantly from the onset of exercise.

Influence of exercise intensity and duration

During very intense exercise when oxygen consumption fails to meet energy demands, stored muscle and liver glycogen become the primary energy sources because energy transfer from carbohydrates can occur without oxygen. With the reintroduction of the needle biopsy technique in early 1960s, considerable effort has been devoted to the study of glycogen utilization during exercise as well as the re-establishment of glycogen stores after exercise. A landmark study by Gollnick *et al.* (1974) revealed that muscle glycogen breakdown is most rapid during the early stages of exercise with its rate of utilization being exponentially related to exercise intensity. They also found that slow-twitch muscle fibers were the first to lose glycogen. This was then followed by increased glycogen utilization in fast-twitch muscle fibers. As exercise continues, the rate of muscle glycogen utilization declines and this is then accompanied by an increased contribution of blood-borne glucose degraded from liver glycogen as a metabolic fuel. It is estimated that a two-hour vigorous workout just about depletes glycogen in the liver as well as exercised muscle.

During moderate-intensity exercise, utilization of PCr as an energy source is relatively mild, even at the onset of exercise. Glycogen stored in active muscle supplies almost all the energy in the transition from rest to exercise. As soon as a steady state is attained, energy is then provided through a mixed use of carbohydrates and lipids. Typically, liver and muscle glycogen supply is between 40 and 50 percent of the energy requirement,

whereas the remainder is furnished via the oxidation of lipids. Such energy mixture may vary depending on the intensity of exercise, although it may also be influenced by the training status of an individual and dietary intake of carbohydrates. For example, a trained individual is able to use proportionally more fat as energy at a submaximal workload, and those who consume a diet low in carbohydrates may force their body to use relatively more fats instead of carbohydrates. As exercise continues, muscle glycogen stores diminish progressively. Consequently, as blood glucose from liver glycogen becomes the major supplier of carbohydrate energy, the relative contribution of fat to the total energy provision also increases. With glycogen depletion, the maximal steady-state exercise intensity that can be sustained decreases accordingly. This is mainly caused by a slower rate of energy production via fat metabolism. As bodily glycogen decreases significantly, blood glucose also falls because the liver's glucose output fails to match the rate of glucose uptake by exercising muscles. **Hypoglycemia** is said to occur when blood glucose concentration is lower than 2.5 mmol l^{-1} or 45 mg dL^{-1}. This condition may occur during strenuous exercise that lasts for close to or more than two hours. Table 9.1 illustrates the percentage of energy derived from the four major sources of fuel during prolonged moderate-intensity exercise (i.e., 65 to 75 percent VO_2max) in trained individuals.

Liver sources of carbohydrate

During exercise when utilization of carbohydrates accelerates, an increased release of glucose from the liver is functionally important to maintain blood glucose homeostasis and to possibly attenuate muscle glycogen depletion. It remains subject to debate whether the increased availability of blood glucose helps in sparing the use of muscle glycogen. However, it appears that once hypoglycemia is induced, muscle glycogen utilization is likely to accelerate. The increased contribution of liver glycogen is a universal phenomenon that was revealed nearly 50 years ago. Early studies have demonstrated that the release of glucose from liver glycogen was accelerated three to six times that of resting values during muscular work. Over the following two to three decades there has been repeated evidence suggesting that **hepatic glucose output** can increase by two- to three-fold during moderate exercise and up to seven- to ten-fold during vigorous exercise.

The intensity and duration of exercise are the important factors that determine the source and quantity of glucose released by the liver. During moderate exercise (<60 percent VO_2max), the blood glucose level remains relatively constant despite an increase in glucose utilization by exercising muscles. At this intensity, a fall in blood glucose will not occur unless exercise is prolonged for several hours. The level of blood glucose reflects a

Table 9.1 Percentage of energy derived from the four major sources of fuel during moderate-intensity exercise at 65 to 75 percent VO_2max

Energy sources	*% of energy expenditure*				
	Onset of exercise	*1st hour*	*2nd hour*	*3rd hour*	*4th hour*
Muscle glycogen	45	35	22	12	0
Blood glucose	5	13	23	30	40
Plasma-free fatty acids	25	32	39	46	52
Muscle triglycerides	25	20	16	12	8

Note
Data are the estimated percentages of energy expenditure based on studies that used endurance athletes.

balance between hepatic glucose output and muscular glucose utilization. Hence, at moderate intensity, an exercise-induced rise in hepatic glucose output is able to match the increased glucose utilization. In contrast, if exercise becomes more intense (>60 percent VO_2max), blood glucose concentrations increase, especially during the early phase of exercise, and such an increase is more pronounced at higher exercise intensities (Hargreaves and Proietto 1994). This mismatch may be due to the fact that hepatic glucose output exceeds glucose uptake by working muscles. It has been considered that the production of glucose from the liver is not totally regulated by feedback mechanism, which is fundamentally important in maintaining homeostasis. In this case of over-production of hepatic glucose, the finding has been attributed to increased efferent signals of the central nervous system that regulate hepatic glucose metabolism (Kjaer *et al.* 1987).

Gluconeogenesis: generating glucose in the liver

An increase in liver glucose output may be brought about by an enhancement of glycogenolysis and **gluconeogenesis**. While glycogenolysis is a relatively simple process that involves glycogen breakdown into glucose, gluconeogenesis entails a relatively complex pathway that involves the use of non-glucose molecules such as amino acids or lactate for the production of glucose in the liver. This "new" glucose can then be released into the blood and transported back to skeletal muscles to be used as an energy source. This internal production of glucose may be viewed as the secondary resort from which the body obtains glucose. Figures 9.1 and 9.2 demonstrate the two different processes of gluconeogenesis in which glucose is generated from its precursors lactate and alanine, respectively. In general, glycogenolysis appears to respond more quickly and to contribute more of the total hepatic glucose output during exercise. During the first 30 minutes of exercise of either moderate or heavy intensity, most of the glucose released by the liver is derived from hepatic glycogenolysis. Gluconeogenesis, however, seems to be more responsive to the length of exercise and to play a more important role during the later phase of prolonged exercise. In a series of experiments using dogs, Wasserman *et al.* (1988) found that the relative contribution of gluconeogenesis to the total hepatic glucose output was only 15 percent during the first 60 minutes of exercise. However, it reached 20 to 25 percent when exercise continued for another hour and a half.

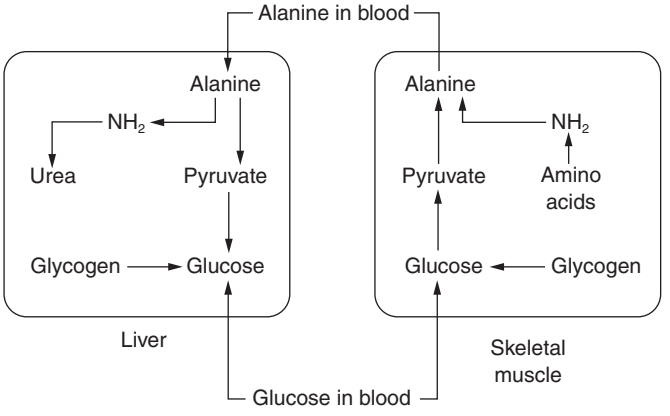


Figure 9.1 An example of gluconeogenesis during which the muscle-derived lactate is converted into glucose and this newly formed glucose then circulates back to muscle

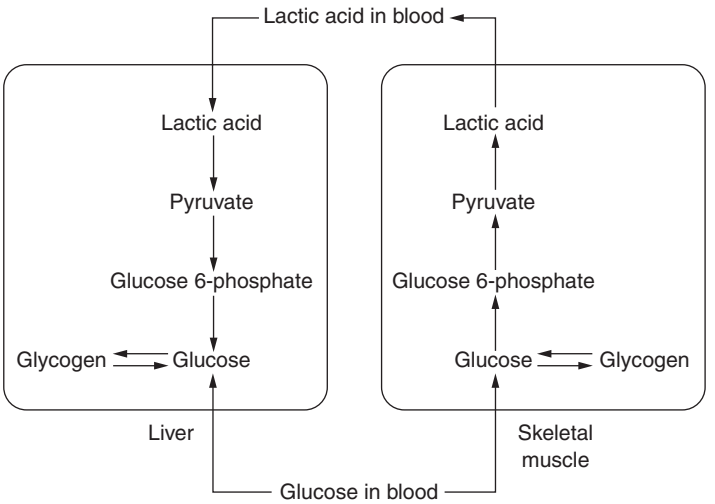


Figure 9.2 An example of gluconeogenesis during which the muscle-derived alanine is converted into glucose and this newly formed glucose then circulates back to muscle

Exercise intensity can influence the type of gluconeogenic precursors used to produce glucose in the liver. Glycerol, lactate, and amino acid are the three major precursors that may be converted into glucose via gluconeogenesis. It is generally believed that when exercise is performed at an intensity level below **lactate threshold**, an intensity above which the production of lactate will increase sharply, glycerol is the primary molecule used for gluconeogenesis. As exercise intensity approaches and exceeds the lactate threshold, more lactate becomes available for producing glucose in the liver. Such different uses of gluconeogenic precursors at different exercise intensities make sense in that glycerol is a product of lipolysis and fat utilization increases during exercise of low to moderate intensity. However, as intensity increases more glycogen is degraded, thereby producing more lactic acid. An increased contribution of amino acids to gluconeogenesis would be seen particularly during vigorous exercise that lasts for a prolonged period of time. In this case, both muscle and liver glycogen stores decrease significantly and there is a necessity to produce more glucose in order to prevent the occurrence of hypoglycemia.

Regulation of muscle and liver glycogen degradation

Muscle glycogen is the primary carbohydrate fuel for most types of exercise and the heavier the exercise intensity, the faster glycogen is degraded. The three major factors that control muscle glycogen breakdown are (1) hormone **epinephrine**, (2) activity of **glycogen phosphorylase**, and (3) substrate availability. It is generally considered that epinephrine plays the most important role in mediating muscle glycogen degradation. The major action of epinephrine is to facilitate glycogenolysis. This catabolic action is initiated by second messengers, which activate protein kinases needed for glycogenolysis, and plasma epinephrine is responsible for the formation of cyclic AMP when bound with β adrenergic receptors (Hargreaves 2006). Glycogen phosphorylase is an enzyme that catalyzes the first step of glycogen breakdown and is responsible for supplying individual

glucose molecules to the glycolytic pathway for producing ATP. In the resting state, this enzyme exists primarily in the inactive b form, and the activity of which can be stimulated if energy demand increases. In response to muscle contraction or stimulation by epinephrine, the phosphorylase b inactive form is converted to the phosphorylase a active form. However, under the influence of insulin, activated phosphorylase can become deactivated. This will then reduce the availability of glucose. Substrate availability will also affect the rate of glycogen degradation. Early studies have shown that increases in pre-exercise muscle glycogen result in enhanced muscle glycogen utilization during exercise. It was proposed that glycogen can bind to glycogen phosphorylase and, in doing so, increase its activity. Availability of blood-borne substrates such as glucose may also influence muscle glycogenolysis. Coyle *et al.* (1991) found that an increase in blood glucose as a result of intravenous infusion of glucose resulted in a decrease in muscle glycogen utilization. However, when blood glucose was brought down, no alteration in glycogen utilization was observed.

The main function of liver glycogen is to maintain blood glucose homeostasis by degrading into glucose when blood glucose levels decrease. Liver glycogen degradation is mainly regulated by insulin and glucagon, the two hormones that work against each other in regulating blood glucose concentrations. Insulin promotes glycogen synthesis, whereas glucagon facilitates glycogen degradation. Both hormones exert their glucoregulatory function in the liver. By manipulating insulin and glucagon levels with the infusion technique, studies have demonstrated favorable responses of hepatic glucose output (Wasserman *et al.* 1984, 1989). In other words, when plasma insulin was made to decrease or when plasma glucagon was made to increase, there was a resultant increase in hepatic glucose production. The greatest effect on hepatic glucose uptake was observed when there was a simultaneous decrease in glucagon and an increase in insulin (Marker *et al.* 1991). Liver glycogenolysis may also be subject to the control by autonomic/adrenergic activities. In a study that used leg as well as combined arm and leg exercise, Kjaer *et al.* (1991) observed a positive correlation between plasma catecholamines and hepatic glucose output. In addition, in an animal study in which the adrenal medulla was removed, Richter *et al.* (1981) and Sonne *et al.* (1985) found a reduced liver glycogenolysis and hepatic glucose output. These findings suggest that epinephrine and norepinephrine also play a role in the exercise-induced increase in glucose output from the liver.

Regulation of glycolysis and the Krebs cycle

As discussed in Chapter 8, glycolysis and the aerobic pathway containing the Krebs cycle are the two pathways in which glucose is further metabolized with or without oxygen. Each process consists of a series of sequential chemical reactions and each reaction is catalyzed by a specific enzyme. The rate of glycolysis is controlled by the activity of **phosphofructokinase** (PFK). PFK catalyzes the third step of glycolysis. When exercise begins, increases in ADP and Pi levels activate PFK, thereby accelerating glycolysis. PFK is also activated by an increase in cellular levels of hydrogen ions and ammonia. The Krebs cycle, like glycolysis, is also subject to enzymatic regulation. Among numerous enzymes involved, **isocitrate dehydrogenase** (IDH) is thought to be the rate-limiting enzyme in the aerobic pathway. This enzyme catalyzes a reaction during the early phase of the Krebs cycle. Similar to PFK, the enzyme is stimulated by ADP and Pi and inhibited by ATP. IDH is also sensitive to the change in cellular levels of calcium. McCormack and Denton (1994) have found that an increase in calcium ions in mitochondria stimulates IDH. This finding is in congruence with the concept that an increase in calcium ions in muscles is essential to initiate muscle contraction that requires energy.

Lipid metabolism

Triglycerides represent another major source of energy stored primarily in adipose tissue, although they are also found in muscle tissue. As discussed in Chapter 2, a triglyceride molecule comprises glycerol and three fatty acids that can vary in terms of how many carbons each fatty acid contains. Via lipolysis, a triglyceride is split to form glycerol and three independent fatty acids. These products can then enter metabolic pathways for energy production. Despite the large quantity of lipids available as fuel, the processes of lipid utilization are slow to be activated and proceed at rates significantly lower than the processes controlling carbohydrate utilization. However, lipids are an important segment of energy substrates used during prolonged exercise or during extreme circumstances such as fasting or starvation when carbohydrate stores decline significantly. Even small increases in the ability to use lipids as fuel during exercise can help slow muscle glycogen and blood glucose utilization and delay the onset of fatigue. An increase in the ability to use lipids can be realized by the improved oxidative capacity of skeletal muscle following endurance training.

Energy sources from lipids

Three lipid sources supply energy: (1) fatty acids released from the breakdown of triglycerides; (2) circulating plasma triglycerides bound to lipoproteins; and (3) triglycerides within the active muscle itself. Unlike carbohydrates, which can yield energy without using oxygen, fat catabolism is purely an aerobic process that is best developed in the heart, liver, and slow-twitch muscle fibers. Most fat is stored in the form of triglycerides in fat cells or adipocytes, but some is stored in muscle cells as well. The major factor that determines the role of fat as an energy substrate during exercise is its availability to the muscle cell. In order for fat to be oxidized, triglycerides must first be cleaved to three molecules of free fatty acid (FFA) and one molecule of glycerol. This process, namely lipolysis, occurs through the activity of **lipase**, an enzyme found in the liver, adipose tissue, muscle, as well as blood-vessels. Lipolysis is modulated by the hormones epinephrine and norepinephrine. As such, this process is considered intensity dependent because the release of these hormones increases as exercise intensity increases. It must be noted that lipolysis and oxidation are the two separate processes of fat utilization. The latter process is facilitated during low- to moderate-intensity exercise in which the production of lactic acid is low.

Preparatory stages for fat utilization

Following lipolysis, two additional processes must also occur before FFA can be combusted: (1) mitochondria transfer, and (2) **ß–oxidation**. The oxidation of fatty acids occurs within the mitochondria. However, long-chain fatty acids are normally unable to cross the inner mitochondrial membrane due to their molecular size. This would then require a membrane transport system consisting of protein carriers. The carrier molecule for this system is **carnitine**, which is synthesized in human from amino acids lysine and methionine and is found in high concentration in muscle. Under the assistance of carnitine and an enzyme called **carnitine palmitoyl transferase (CPT)**, fatty acids can be brought from cytoplasm into mitochondria. Upon entry into the mitochondria, fatty acids undergo another process called *ß*–oxidation. *ß*–oxidation is a sequence of reactions that reduce a long-chain fatty acid into multiple two-carbon units in the form of acetyl-CoA (Figure 9.3). This process may be viewed as being analogous to glycolysis, the first stage of the oxidative pathway for glucose in which a

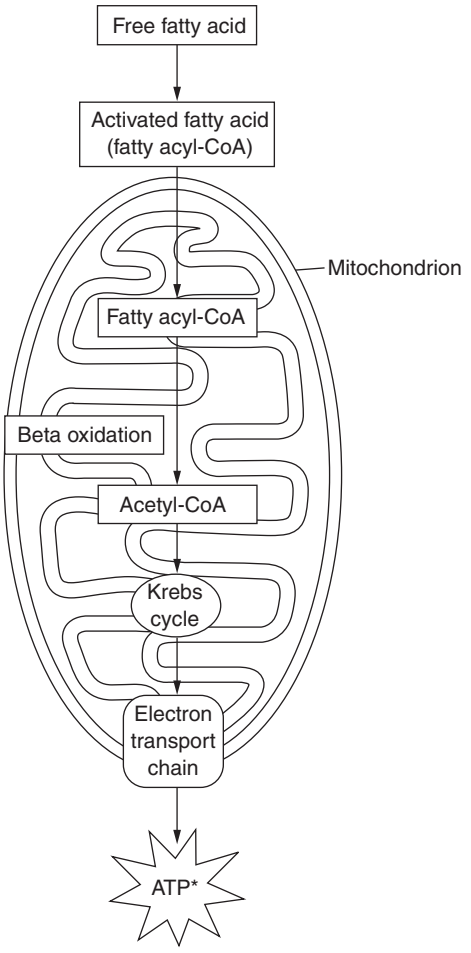


Figure 9.3 Illustration of *ß*–oxidation

Source: Powers and Howley (2018). Used with permission.

glucose molecule is converted into two molecules of acetyl-CoA. Once formed, acetyl-CoA then becomes a fuel source for the Krebs cycle and leads to the production of ATP within the electron transport chain.

Influence of intensity and duration on fat utilization

Fat oxidation is influenced by exercise intensity and duration. Romijn *et al.* (1993) found that during exercise at 25 percent VO_2max, 90 percent of the total energy is furnished via oxidation of plasma FFA and muscle triglycerides. The relative contribution of fat to total oxidative metabolism decreases as exercise intensity increases. However, such decrease in the relative contribution of fats is relatively minor compared with an increase in oxygen consumption. Therefore, despite a decrease in relative contribution, there is actually an increase in the amount of fats being oxidized until the intensity reaches a value close to one's lactate threshold (or ~60 percent VO_2max). A number of recent

studies have found that the intensity at which the highest fat oxidation (**Fat_{max}**) is observed ranges from 55 to 72 percent VO_2max (Achten *et al.* 2002, 2004). For example, by testing with multiple levels of intensity, Achten *et al.* (2002) found that Fat_{max} in endurance-trained men occurred at about 64 percent VO_2max, with maximal rates of ~0.6 g min^{-1} observed. This same research group also demonstrated that Fat_{max} was lower in untrained as compared to trained individuals and men had lower Fat_{max} than women (Venables *et al.* 2005). In our laboratory, we also demonstrated that the intensity of maximal fat oxidation corresponds well with lactate threshold (Kang *et al.* 2007), suggesting that in order to obtain the maximal fat oxidation, a comparatively more intense exercise should be chosen. When exercise is performed at intensity above the lactate threshold, fat oxidation decreases significantly. This may be the result of increased carbohydrate utilization and/or the accumulation of lactic acid that may serve to inhibit fat utilization.

As shown in Table 9.1, as a steady-state exercise of light to moderate intensity continues, the contribution of fat to the total oxidative metabolism increases progressively. Using a prolonged exercise protocol in which exercise lasted for four hours, earlier studies have demonstrated a progressive decrease in respiratory exchange ratio, signifying a steady increase in fat combustion (see Chapter 12 for further details on the concept and application of the respiratory exchange ratio). It has been estimated that the relative contribution of fat may account for as much as 80 percent of total energy expenditure during prolonged exercise. The progressive increase in fat utilization over time is due to a concomitant decrease in glycogen stores as a result of prolonged exercise. This reduction in carbohydrate energy substrates will trigger a release of glucoregulatory hormones such as glucagon, cortisol, and growth hormone. These hormones function to stimulate the breakdown of lipids in response to reduced carbohydrate stores. Refer to the later sections of this chapter for more information with regard to the hormonal regulation of fuel utilization.

Interaction between carbohydrate and fat utilization

The utilization of carbohydrates and fats are not two separate processes. Instead they are coordinated, and the utilization of one substrate would be affected by the availability of the other. It has been suggested that carbohydrate availability during exercise modulates the level of lipolysis and fat oxidation. Previous studies found that ingesting high-glycemic carbohydrates prior to exercise significantly blunts the release of fatty acids from adipose tissue and thus oxidation of long-chain fatty acids by skeletal muscle (Coyle *et al.* 1997, De Glisezinski *et al.* 1998). As carbohydrate substrates decline, such a suppressive effect of carbohydrate on fat utilization is withdrawn. Conversely, an elevation in blood-free fatty acids may suppress carbohydrate utilization. This was initially evidenced in a study where subjects were infused with triacylglycerol and demonstrated a consequential decrease in muscle glycogen breakdown following an endurance exercise (Costill *et al.* 1977). A reduction in carbohydrate utilization was also observed when subjects were fed with fat in conjunction with heparin that helps facilitate lipolysis (Vukovich *et al.* 1993).

Such interaction between carbohydrates and fats may be explained by the classical glucose–fatty acids cycle discovered by British biochemist Philip Randle over 40 years ago. As shown in Figure 9.4, with an increase in plasma fatty acid concentration, there is an increase in fatty acid entry into the cell and subsequent increase in β–oxidation in which fatty acids are broken down into acetyl-CoA. An increased concentration of acetyl-CoA will then inhibit several key enzymes that catalyze carbohydrate degradation (i.e., PDH and PFK) as well as cellular glucose uptake (i.e., HK). Randle's hypothesis has

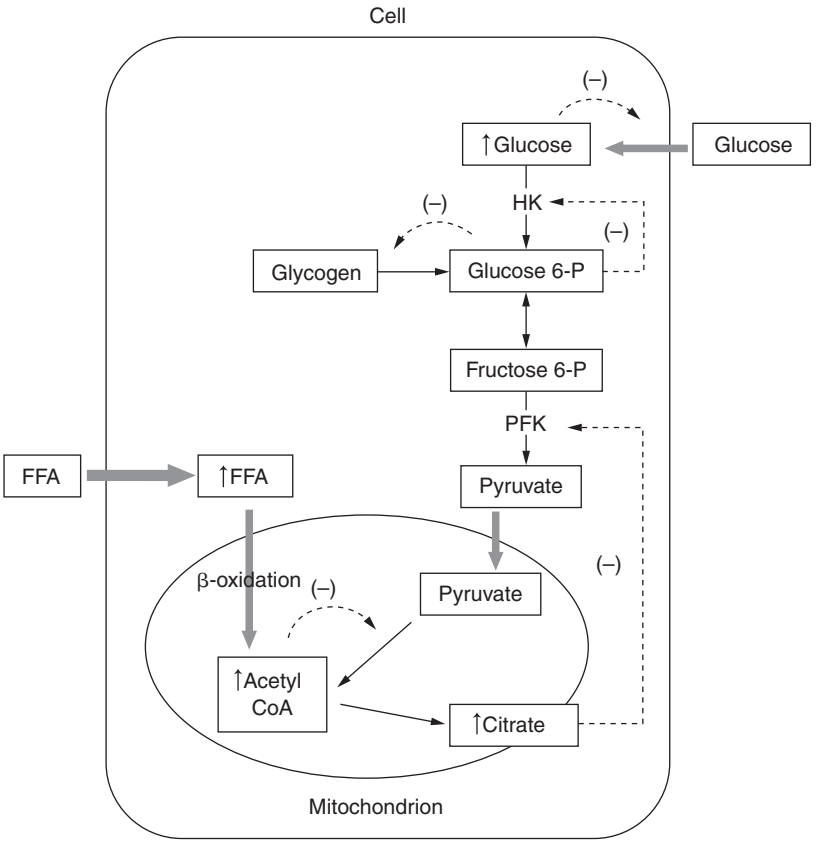


Figure 9.4 Schematic illustration of glucose and fatty acid cycle or Randle cycle

been used to explain how the mitochondrial adaptations resulting from endurance training help promote lipid oxidation and thus spare glycogen utilization in skeletal muscle during exercise.

Regulation of lipolysis and fat oxidation

The interaction between carbohydrates and fats discussed earlier may be further ascribed to the effect of hormones that regulate fuel utilization. In order to be metabolized, stored fat must first undergo lipolysis in which triglycerides are degraded to fatty acids and glycerol. The resulting fatty acids are then converted into acetyl-CoA and enter the Krebs cycle for further metabolism. Adipose tissue lipolysis is controlled by the hormone-sensitive lipase, which breaks the bonding of triglycerides so that fatty acids and glycerol are formed. This enzyme is regulated by hormones of insulin, glucagon, catecholamines, cortisol, and growth hormone. Release of these hormones increases when bodily carbohydrates decrease except for insulin. Of these hormones, insulin is the only one that inhibits lipolysis, whereas all the others function as a stimulator. Of those stimulating hormones, catecholamines are the most potent stimulator of lipolysis during exercise. Catecholamines are bound with the β-adrenergic

receptors, causing a production of a second messenger cyclic AMP. This later product then triggers a series of chemical events through which the activity of hormone-sensitive lipase becomes activated. On the other hand, insulin can reverse the effects of lipolytic hormones. It is thought that insulin suppresses lipolysis by either decreasing cyclic AMP concentration or inhibiting enzymes needed to activate hormone-sensitive lipase.

Regulation of fat utilization requires fatty acids to be transported into the mitochondria where fat can be oxidized. In this context, the mass of mitochondria and oxygen delivery are important factors in determining rates of fat utilization. The process in which fatty acids are transported across the mitochondrial membrane is mainly controlled by the activity of carnitine palmitoyl transferase (CPT). As discussed earlier, CPT is part of the transport system needed for long-chain fatty acids to enter the mitochondrion where oxidation takes place. In this context, it makes sense that CPT plays an important role in the control of fat oxidation. CPT is regulated by **malonyl-CoA**, an intermediate in fatty acid synthesis. An increase in malonyl-CoA content inhibits the activity of CPT, thereby reducing fat utilization. During high-intensity exercise, the high rate of glycogenolysis increases the amount of acetyl-CoA in the muscle cell, and some of this acetyl-CoA is converted into malonyl-CoA. This increased malonyl-CoA then suppresses CPT and thus reduces the transport of fatty acids into the mitochondria. Conversely, as carbohydrate energy sources are depleted, such inhibitive effects from malonyl-CoA on CPT attenuate due to reduced glycogenolysis. Consequently, the activity of CPT is augmented and fat utilization is enhanced. Besides malonyl-CoA, Starritt *et al.* (2000) suggested that a reduction in pH (or an increase in acidity) associated with high-intensity exercise would also serve as an inhibitor to the activity of CPT.

Tissues that have rich mitochondrial and capillary content such as the heart and liver are highly adapted for fat utilization, whereas brain and red blood cells rely almost exclusively on glycolysis for energy. In skeletal muscle, fast-twitch muscle fibers are limited in utilizing fat due to its low volume of mitochondria as well as less than optimal blood supply. In contrast, slow-twitch muscle fibers are highly capable of oxidizing fat in that they are rich in mitochondria and capillaries.

Protein and amino acid metabolism

Skeletal muscle constitutes approximately 40 percent of the body weight and is the second-largest store of potential energy in the body after fat. However, proteins and amino acids serving as energy substrates are a relatively uncommon topic. This is because amino acids contribute only a minor portion (i.e., 5 to 15 percent) of the total energy consumed during exercise. Unlike carbohydrates and fats, which may be stored as energy substrates, there are virtually no inert amino acids that are designated for such a purpose. However, it must be recognized that during fasting and starvation, catabolism of proteins to amino acids and conversion of amino acids into energy are very important processes in maintaining the levels of blood glucose essential for brain and kidney function. It has been reported that gluconeogenesis which uses amino acids increases every morning in response to the fall in glycogen stores. In the past decade or so, researchers have realized that even a minor increase in protein consumption is important in conditions of high-energy demands over a prolonged period of time. There is growing evidence especially with more recent research on **branched-chain amino acids** such as leucine, valine, and isoleucine to suggest that protein serves as energy fuel to a much greater extent than previously believed.

Protein metabolism during exercise

Protein metabolism includes its degradation and synthesis. Unlike carbohydrates and fats, the magnitude of protein degradation often occurs to a smaller extent. However, it can be increased significantly when exercise is performed at high intensity for a prolonged period of time. There are two classes of protein in skeletal muscle: contractile and non-contractile. While contractile-related proteins are responsible for muscle contraction, non-contractile-related proteins are essential for other cellular functions. In humans, contractile and non-contractile proteins comprise 66 and 34 percent of total muscle protein, respectively. Remember that a protein molecule comprises chains of amino acids. As such, the amino acids tyrosine and phenylalanine have been used as indicators of non-contractile protein degradation. In an early study in which experimental protocol entailed 40 minutes of exercise performed at different intensities, Felig and Wahren (1971) demonstrated a greater release of tyrosine and phenylalanine as well as alanine during exercise compared with rest, with such an enhanced efflux of metabolites being greater at higher exercise intensity. Later, Babij *et al.* (1983) also observed a direct linear relationship between exercise intensity and oxidation of leucine, one of the three branched-chain amino acids. In terms of the metabolism of contractile proteins, the measurement of 3-methyhistidine (3-MH) in the urine has been the most widely used approach in reflecting the degradation of contractile proteins, although this parameter may also be determined via the blood. Through a thorough review of the literature, Dohm *et al.* (1987) came to the conclusion that the production of this catabolic index of contractile protein decreases during exercise. However, there are studies reporting an increase in the efflux of 3-MH during recovery. Taken together, these findings suggest that the integrity of contractile protein remains unaffected during exercise when muscle contraction is in demand; however, this is not the case during recovery. The mechanism responsible for the divergent response in 3-MH between exercise and recovery is unclear.

The assessment of protein degradation along with protein synthesis will provide an idea as to whether those who exercise will need an extra protein in order to prevent a loss in lean body mass. Such an assessment may be accomplished by determining **nitrogen balance**. Protein contains nitrogen, and the body cannot oxidize the nitrogen component. Consequently, nitrogen atoms combine with hydrogen to form urea to be excreted via the kidneys. Nitrogen balance involves assessing the relationship between the dietary intake of protein and protein that is degraded and excreted. Nitrogen balance is said to occur when protein intake equals the amount excreted. A positive nitrogen balance suggests that protein intake exceeds protein output and the excessive protein may have been used to repair damaged tissue and/or to synthesize new tissue. A positive nitrogen balance is expected in children, pregnant women, and body builders (Table 9.2). On the other hand, a negative nitrogen balance indicates that protein loss is greater than its intake and this type of nitrogen imbalance is often manifested in individuals who are on a weight loss diet or with poor nutrition or eating disorders (Table 9.2). A negative nitrogen balance may also occur in athletes who are overly trained because the protein that is lost may have been degraded and used for energy due to exercise. Protein synthesis decreases during exercise and this finding has been universally demonstrated. This decreased protein synthesis together with increased protein degradation clearly suggests that those who are heavily trained would experience an augmented protein loss and thus require a higher protein intake on a regular basis. Lemon *et al.* (1992) administered two levels of dietary protein in a group of novice body builders who underwent a month of resistance training. They found that a majority of those who are on the lower protein intake (i.e., 0.99 g kg^{-1} per

Table 9.2 Expected nitrogen balance status among various individuals

Examples	*Nitrogen intake*	*Nitrogen output*	*Nitrogen balance*
Individuals on weight loss diet or with poor nutrition	6.4 g	8.0 g	–1.6 g
Healthy individuals on normal diet	11.2 g	11.2 g	0 g
Pregnant women, children, body builders	12.8 g	10.4 g	+2.4 g

day) experienced a negative nitrogen balance, whereas all of those who are on the high protein intake (i.e., 2.62 g kg^{-1} per day) achieved a positive nitrogen balance. It was their further calculation that nitrogen balance occurs at 1.43 g kg^{-1} per day. The recommended daily allowance (RDA) for protein is 0.8 g kg^{-1} per day for a healthy adult. However, in light of augmented protein catabolism associated with heavy exercise, it is suggested that those with endurance training should consume protein between 1.2 and 1.4 g kg^{-1} per day and those who resistance train may benefit from consuming ~1.6 g kg^{-1} per day (Fielding and Parkington 2002).

While net protein breakdown occurs during exercise, protein synthesis is believed to predominate during the recovery period. It has been evidenced that whole body protein breakdown is generally reduced following aerobic endurance exercise, while whole body protein synthesis is either increased or unchanged (Tipton and Wolfe 1998). During resistance exercise, protein breakdown was also observed in exercised muscle and this catabolic response persisted in the immediate recovery period (Tipton and Wolfe 1998). However, over the next 24 to 48 hours, protein synthesis appeared to predominate and outpace protein degradation. Such positive protein balance is thought to be due more to the stimulation of synthesis rather than a decrease in breakdown (Wolfe 2006). This is especially so if adequate amino acids are available. Eccentric exercise, such as lowering weights during resistance exercise or running downhill, puts tremendous stress on muscle tissue, and often induces muscle soreness over the following days. The muscle fiber micro-tears are believed to be the underlying cause of muscle soreness, which is referred to as **delayed onset of muscle soreness (DOMS)** because its onset is usually delayed for one to two days.

Protein synthesis

The body uses amino acids to synthesize proteins. These amino acids come from the **amino acid pool**, which is a grand mixture of amino acids available in the cell derived from dietary sources or the degradation of protein. The information that dictates which amino acids are needed, and in what order they should be combined, is contained in stretches of DNA called genes. When a protein is needed, the process of protein synthesis is activated. As shown in Figure 9.5, the first step in protein synthesis involves copying or transcribing the DNA's code from the gene into a molecule of messenger RNA (mRNA). This process is called **transcription**. The mRNA then takes this information from the nucleus of the cell to ribosomes in the cytosol where proteins are made. Here the information in mRNA is translated through another type of RNA, called transfer RNA (tRNA). Transfer RNA reads the code and delivers the needed amino acids to form a polypeptide chain. This process is called **translation**. One by one, amino acids join via peptide bonds to form growing polypeptide chains. When translation is completed, newly formed polypeptides detach from ribosomes and undergo further chemical modifications before achieving their final protein structure and function.

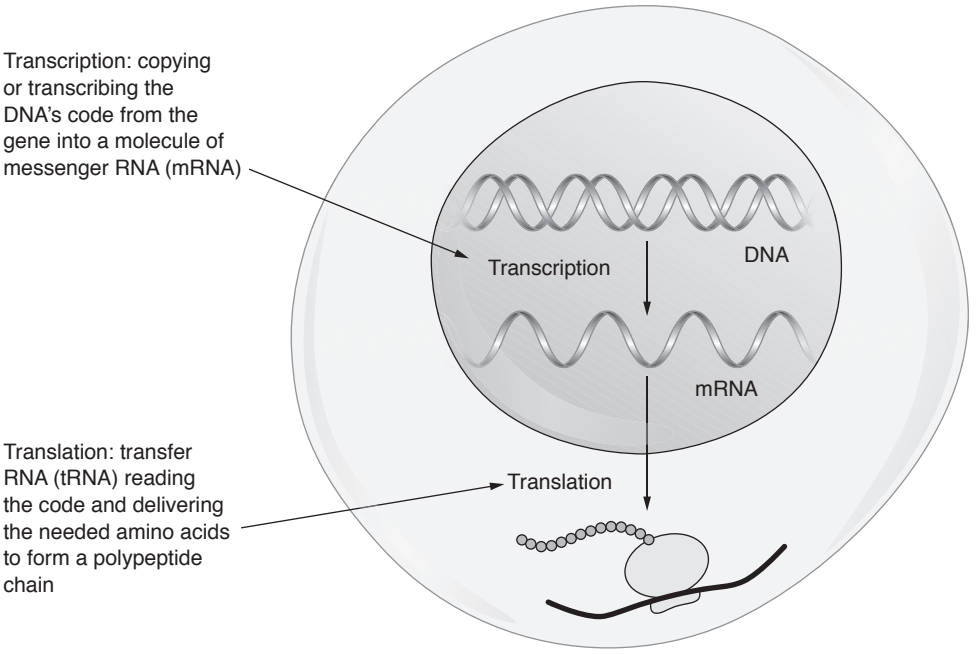


Figure 9.5 Protein synthesis: transcription and translation

During the synthesis of a protein, a shortage of one needed amino acid can stop the process. Just as on an assembly line, if one part is missing, the line stops – a different part cannot be substituted. If the missing amino acid is nonessential amino acid, it can be synthesized in the body and protein synthesis can continue. If the missing amino acid is an essential amino acid, the body cannot break down some of its own proteins to obtain this amino acid. If an amino acid cannot be supplied, protein synthesis will stop. Animal foods are generally better sources of protein because they provide enough of all the amino acids needed to build human proteins. Plant sources of protein, however, are generally low on one or more of the essential amino acids and thus are not the preferred choice if someone is seeking a rapid gain in muscle mass.

Energy metabolism of amino acids

There are three principal sources of amino acids for energy metabolism: (1) dietary protein, (2) free amino acid pool, and (3) **endogenous** tissue protein. Dietary protein is a relatively minor source of amino acids because it is not a common practice to consume a large protein meal prior to exercise. The free amino acid pool existing in muscles and blood is also very small compared with amino acids derived from the degradation of tissue protein. It has been estimated that the intra-muscular amino acid pool constitutes less than 1 percent of the metabolically active amino acids. Consequently, the most important source of amino acids comes from endogenous protein breakdown (Dohm *et al.* 1987).

The catabolism of amino acids requires the removal of the amino group (the nitrogen-containing portion) by transamination or oxidative deamination. Transamination is a

common route for the exchange of nitrogen in most tissues including muscle and involves the transfer of an amine from an amino acid to another molecule. A typical example is where the amine is transferred from glutamate to pyruvate to produce alanine, which may then be utilized to produce glucose in the liver via a process called the alanine cycle, as shown in Figure 9.2. The process of deamination occurs in the liver and is responsible for converting the nitrogen residue into waste product urea that can be excreted from the kidneys.

The remaining carbon skeleton may then be converted into various intermediates of the Krebs cycle which is common to both carbohydrate and fat metabolism. As shown in Figure 9.6, amino acids may give rise to pyruvate, acetyl CoA, and Krebs cycle intermediates, such as oxaloacetate, fumarate, succinyl–CoA, and α-ketoglurate, all of which may be oxidized via the Krebs cycle. Another way by which amino acids contribute to energy metabolism is to be converted into glucose via gluconeogenesis and this glucose is then used for generating energy or preventing hypoglycemia. This process has been discussed above in the context of deamination and transamination. As shown in Figure 9.6, alanine is first produced from pyruvate via transamination in active skeletal muscle and then travels to the liver via circulation. Upon entry into the liver, alanine becomes pyruvate via deamination. Gluconeogenesis then converts the remaining carbon skeleton of alanine into glucose, which then enters the blood for use by active muscle. This gluconeogenic process helps in maintaining blood glucose homeostasis during fasting and starvation. It also assists in prolonged exercise as additional energy fuel. It has been estimated that the alanine–glucose cycle can generate up to 15 percent of the total energy requirement during prolonged exercise (Paul 1989).

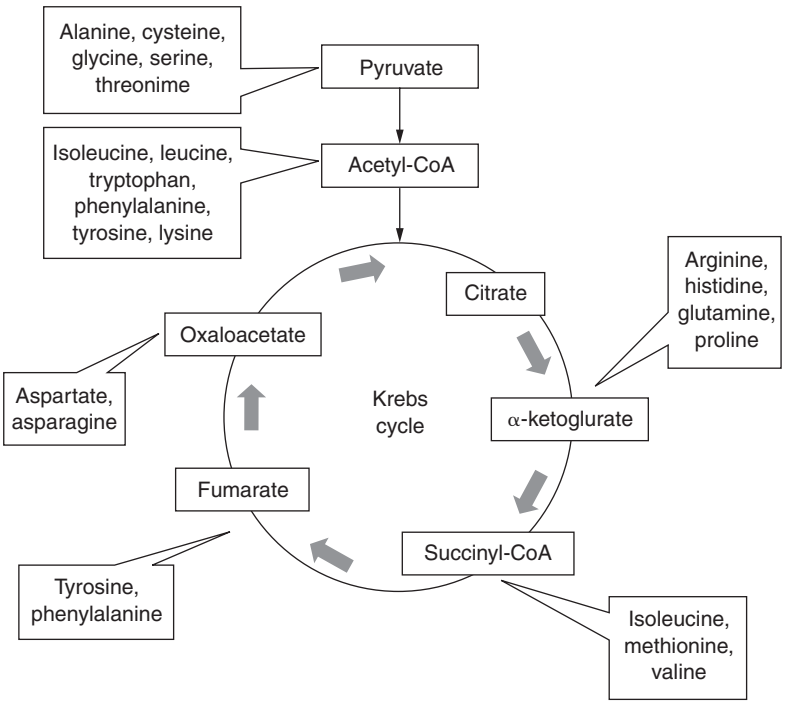


Figure 9.6 Major metabolic pathways for various amino acids following removal of the nitrogen group by transamination or deamination

Metabolic role of branched-chain amino acids

Leucine, isoleucine, and valine are the three branched-chain amino acids (BCAAs) that have attracted a great deal of attention in terms of their role in bioenergetics. They are essential amino acids which cannot be synthesized in the body. Thus, they must be replenished via diet. BCAAs are unique in that they are catabolized mainly in the skeletal muscle. Like other amino acids, the first step in the metabolism of BCAAs is removal of the amino group so that the remaining carbon skeleton may be further oxidized. This transamination results in a production of glutamate, which can then donate a nitrogen-containing portion to pyruvate to form alanine. The oxidative pathway for the remaining carbon skeleton takes place in the mitochondria. It involves decarboxylation which removes a carboxyl group so that acetyl-CoA can be formed for use in the Krebs cycle or gluconeogenesis. Supplementation of BCAAs has been claimed to enhance exercise performance in a variety of ways. They can (1) serve as additional energy fuel, (2) enhance protein synthesis, (3) prevent or attenuate the excessive loss of protein, and (4) help in improving the function of neurotransmitters, thereby reducing the feeling of fatigue. More detailed information regarding the efficacy of using BCAAs for performance enhancement may be found in Chapter 11.

Regulation of protein synthesis and degradation

Protein synthesis and degradation are mainly regulated by hormonal secretion, which can be influenced under many circumstances such as exercise, stress, and dietary feeding. Glucagon, cortisol, and catecholamines are found to be mainly associated with protein degradation, whereas insulin, growth hormones, and testosterone are primarily linked to protein synthesis. Thus far, cortisol has been considered the most potent stimulator of protein catabolism or degradation (Graham and Maclean 1992, Rooyackers and Nair 1997). It degrades tissue protein to yield amino acids for glucose synthesis in the liver via gluconeogenesis. As this action helps generate new glucose units, its role during exercise has been largely investigated. Cortisol secretion does not increase very much during early phases of exercise even when exercise is performed at strenuous levels (i.e., >75 percent VO_2max). However, as severe exercise persists, blood cortisol level begins to rise. An appreciable increase in blood cortisol level has been reported to occur at 30 minutes or longer into exercise. This delayed rise in cortisol appears to be just in time because muscle glycogen is likely to reduce significantly during strenuous exercise that lasts for more than 30 minutes. Under the condition where muscle glycogen is low, an increase in cortisol secretion will assist in maintaining a continuous energy supply and glucose homeostasis throughout exercise. In addition to promoting liver gluconeogenesis, cortisol also stimulates lipolysis which alleviates the body's dependence on its stored carbohydrates.

Insulin, growth hormone, and testosterone appear to be the most influential hormones mediating protein synthesis. Insulin is known for its role in regulating plasma glucose homeostasis in response to hyperglycemia. However, in addition to its effect on stimulating blood glucose uptake by peripheral tissues, insulin also promotes the entry of circulating amino acids into certain cells such as skeletal muscle fibers where protein synthesis takes place. As such, insulin is also regarded as an anabolic hormone in terms of protein synthesis. Insulin release can be blunted during exercise when intensity and duration surpass certain thresholds. This is an appropriate response in that a decrease in insulin favors the mobilization of glucose from the liver and fatty acids from adipose tissue, both of which are necessary in maintaining the plasma energy supply and glucose concentration. If exercise were associated with an increase in insulin, blood glucose would be taken up into the tissues at a faster rate, leading to an immediate hypoglycemia.

The effect of growth hormone on protein synthesis is carried out by increasing the membrane transport of amino acids into cells, synthesis of RNA and ribosomes, activity of ribosomes, as well as all other events essential to protein synthesis. Growth hormone administration has also been linked to a diminished amino acid oxidation (Rooyackers and Nair 1997). Growth hormone can act indirectly via enhanced hepatic release of **somatomedins**, which are carried by the blood to target tissues where they induce growth-promoting effects, particularly in cartilage and bone. Because the somatomedins are structurally and functionally similar to insulin, they are referred to as **insulin-like growth factors**. It is particularly intriguing that the blood level of growth hormone increases during vigorous exercise and remains elevated for a certain time after exercise. This elevation in growth hormone during exercise has been found to function similarly as cortisol serving as a lipolytic hormone to maintain blood glucose homeostasis. Growth hormone stimulates fat breakdown and indirectly suppresses carbohydrate utilization. A low plasma glucose concentration can serve to stimulate the release of growth hormone by the anterior pituitary gland.

Testosterone and testosterone analogs such as anabolic steroids are well known for their anabolic effect on protein metabolism. However, the mechanism as to how this hormone regulates protein metabolism remains elusive. The fact that testosterone enhances protein synthesis has been well documented. It remains less certain as to how this anabolic response is accomplished. It has been argued that testosterone affects muscle growth by binding to receptors in cell nuclei and thus enhancing ribonucleic acid content. The latter substance is necessary in carrying out protein synthesis. There is growing evidence to suggest that testosterone may induce muscle hypertrophy by increasing the number of satellite cells in the skeletal muscle (Sinha-Hikim *et al.* 2003). Testosterone may also increase levels of growth hormone that the body releases in response to exercise. Like testosterone, growth hormone increases protein synthesis and thus muscle growth. With regard to women, progesterone seems more potent in stimulating protein synthesis than estrogen. Smith *et al.* (2014) demonstrated an increase in protein synthesis that occurs in postmenopausal women who are treated with progesterone replacement but not with estrogen replacement.

Summary

- Carbohydrates and fats are the two primary sources of energy. Compared to fats, carbohydrates provide energy more quickly, may be used regardless of whether there is oxygen, and serve as the sole source of energy for the central nervous system. It must also be available in order for the body to use fats. As such, carbohydrates are the main source of fuel for most sporting events.
- Muscle glycogen serves as an initial source of energy at the start of strenuous exercise. As exercise continues, degradation of liver glycogen will increase its contribution by providing additional glucose for use by muscle and to prevent hypoglycemia. The liver is also capable of manufacturing new glucose in an effort to maintain glucose homeostasis.
- Preparing carbohydrate and fat molecules for final entry into the metabolic pathway is an important step in energy metabolism. In order to be oxidized, both glucose and fatty acid need to be converted into acetyl-CoA. This is accomplished through glycolysis for glucose and *ß*–oxidation for fatty acid. Both glycolysis and *ß*–oxidation may be viewed as being similar in that these pathways function to ultimately produce such "common" molecules of acetyl-CoA.
- Oxidizing fat depends on the level of exercise intensity. Unlike what is believed, maximal fat oxidation rate occurs at moderate rather than low intensity. This is

because fat oxidation is also the function of absolute caloric expenditure. It is found that intensity near one's lactate threshold or around 60 to 65 percent VO_2max will elicit maximal fat oxidation.

- Protein does not normally participate in energy metabolism and therefore there is no such storage form of protein used for energy like glycogen. However, under the condition where there is a significant decrease in bodily carbohydrates, proteins may be used as fuel. Proteins contribute to energy provision by first being degraded into amino acids; amino acids will then be converted into glucose or various intermediates of the Krebs cycle in order to fulfill their energetic role.
- Leucine, isoleucine, and valine are the three branched-chain amino acids, and their potential roles include (1) serving as additional energy fuel, (2) enhancing protein synthesis, (3) preventing or attenuating the excessive loss of protein, and/or (4) helping in improving the function of neurotransmitters, thereby reducing the feeling of fatigue.
- A key enzyme that regulates muscle glycogen degradation is glycogen phosphorylase. This enzyme is further influenced by the level of ATP, epinephrine concentration, and glycogen stores. Increases in ADP and AMP levels, epinephrine release, and muscle glycogen concentration have been found to stimulate glycogen phosphorylase, thereby glycogenolysis.
- Phosphofructokinase (PFK) and isocitrate dehydrogenase (IDH) are the rate-limiting enzymes that control glycolysis and the Krebs cycle, respectively. The rate-limiting enzymes are ones found earlier in the metabolic pathway and are sensitive to the level of energy substrate availability.
- Utilization of carbohydrates and fats are not two separate processes. Instead they are coordinated, and the utilization of one substrate would be affected by the availability of the other. The interaction between carbohydrates and fats may be explained by the Randle cycle which encompasses chemical pathways that illustrate a potential "competition" between carbohydrates and fats for being used as fuel.
- The primary function of glucose output from the liver is to maintain normal blood glucose concentration, although some of this can also be taken by muscle tissue for use as energy. The hepatic glucose output is well regulated by insulin and glucagon so that there will not be a mismatch between glucose output and utilization under normal circumstances. However, during high-intensity exercise hepatic glucose output can outpace utilization, thereby causing hyperglycemia.
- Both cortisol and growth hormone serve as a stimulus to lipolysis and gluconeogenesis during prolonged exercise when carbohydrate stores decrease significantly. Such catabolic action is important in that it helps prevent hypoglycemia and muscle glycogen depletion.
- Glucagon, cortisol, and catecholamines are found to be mainly associated with catabolism and protein degradation. Insulin, growth hormones, and testosterone are the most influential hormones mediating anabolism and protein synthesis.

Case study: determining fuel utilization during exercise

Steve is a 49-year-old man who is in the process of training for his first marathon to celebrate his fiftieth birthday. He had some previous recreational running experience and completed several 10-kilometer races and two half-marathons. At 5'7" (170 cm) and 184 lb (84 kg), he realizes that losing weight and body fat will help him accomplish his goal of running a marathon. He participated in an indirect calorimetry study at a nearby university. In this study, he underwent a series of metabolic tests at rest and

while running on a treadmill to learn more about his energy expenditure and fuel utilization at different running paces. Table 9.3 records his results from the study.

Table 9.3 Results of Steve's metabolic tests

Running pace (mile/hr)	*Heart rate (b/min)*	*RER*	*Percent energy from fat*	*Percent energy from CHO*	*Total energy output (kcal/min)*	*Fat use (kcal/min)*	*CHO (kcal/min)*
Rest	70	0.77	77.2	22.8	1.5	1.2	0.3
6.0	130	0.87	42.5	57.5	11.8	5.0	6.8
6.5	139	0.89	35.8	64.2	13.5	4.8	8.7
7.0	145	0.91	29.2	70.8	14.4	4.2	10.2
7.5	155	0.93	22.6	77.4	15.3	3.5	11.8
8.0	166	0.95	16.0	84.0	16.4	2.6	13.8

Questions

- How does the percentage of energy from carbohydrates and carbohydrate oxidation rate ($kcal \cdot min^{-1}$) change as running pace increases? Do these changes make sense? Why?
- The data show that as Steve runs faster, the percentage of energy from fat decreases, while the number of $kcal \cdot min^{-1}$ from fat use increases initially and then decreases. Why is there such a divergent response?
- If Steve was able to maintain a running pace at 7.5 miles/hour throughout the entire marathon race, according to this data how many carbohydrates would he have used both in terms of kcal/min and g/min?

Review questions

1 Why is carbohydrate often referred as the most preferable source of energy?
2 How is the use of energy fuels influenced by exercise intensity and duration?
3 In what circumstance will protein be used as an energy fuel?
4 Define the term "gluconeogenesis." How does this process differ from "glycogenolysis"?
5 What is β–oxidation? How does this process differ from lipolysis?
6 Describe how protein joins energy metabolism.
7 Why are branched-chain amino acids considered ergogenic and used widely in sports?
8 Briefly describe the theory of the Randle cycle.
9 How would you prescribe exercise intensity and duration that will help maximize energy expenditure and fat utilization?
10 Define the term Fat_{max}.
11 Why is high-intensity exercise not recommended for weight loss?
12 What would be the major energy fuel (i.e., carbohydrates, fats, and proteins) used under each of the following conditions?

   a After a meal
   b Between meals
   c Prolonged starvation
   d Exercise at low intensity
   e Exercise at high intensity.

13 What would be the major energy system used during each of the following events?

a 100 m sprint run
b 100 m swimming
c 800 m run
d 10 km run
e Marathon.

14 A subject consumes oxygen at 2 liters/min and expires carbon dioxide at 1.8 liters/min while running on a treadmill. Please answer the following questions:

a How many calories per minute is this person expending?
b If he walks at this pace for 30 minutes, what is his total caloric expenditure?
c How much of the energy is derived from carbohydrates?
d How many grams of carbohydrate does he use?

Suggested reading

1 Achten J, Jeukendrup AE (2004) Optimizing fat oxidation through exercise and diet. *Nutrition*, 20: 716–727.
Interventions aimed at increasing fat metabolism could potentially reduce the symptoms of metabolic diseases such as obesity and type-2 diabetes and may have tremendous clinical relevance. Therefore, this article aims to help readers understand various factors, including those associated with exercise and diets, that increase or decrease fat oxidation.
2 Hargreaves MH, Snow R (2001) Amino acids and endurance exercise. *International Journal of Sport Nutrition and Exercise Metabolism*, 11: 133–145.
Protein degradation during exercise is an area that is under-addressed and stimulates many debates. This article provides a comprehensive review on how amino acids are degraded in order to generate energy aside from carbohydrates and fats. Ergogenic properties of some amino acids are also discussed.
3 Holloszy JO, Kohrt WM, Hansen PA (1998) The regulation of carbohydrate and fat metabolism during and after exercise. *Front Bioscience*, 3: D1011–D1027.
This classic review complements the textbook in that it provides more detailed and evidence-based information that can help us understand how carbohydrates and fats are metabolized and how these metabolic processes are regulated during and after exercise.

Glossary

ß–oxidation a sequence of reactions that reduce a long chain fatty acid into multiple 2-carbon units in the form of acetyl CoA.
Amino acid pool a grand mixture of amino acids available in the cell derived from dietary sources or the degradation of protein.
Branched-chain amino acids amino acids that have side-chains with a branch (a carbon atom bound to more than two other carbon atoms), such as leucine, isoleucine and valine.
Carnitine a carrier protein that helps transport long-chain fatty acids from cytoplasm into mitochondria.
Carnitine palmitoyl transferase (CPT) an enzyme that facilitates the action of carnitine.
Delayed onset of muscle soreness muscle soreness caused by muscle fiber tears and usually felt in muscles several hours to days after unaccustomed or strenuous exercise.
Endogenous produced or growing within an organism, tissue, or cell.

Epinephrine a hormone from adrenal medulla that facilitates glycogen degradation.

Fat_{max} the exercise intensity where fat oxidation rate peaks.

Gluconeogenesis a metabolic pathway that involves the use of non-glucose molecules such as amino acids or lactate for the production of glucose in the liver.

Glycogen phosphorylase a key enzyme that regulates glyogenolysis or glycogen degradation.

Hepatic glucose output glucose release from liver glycogen degradation.

Hypoglycemia a condition that occurs when blood glucose concentration is too low.

Insulin-like growth factors also referred to as somatomedins (see Somatomedins).

Isocitrate dehydrogenase a rating-limiting enzyme that regulates Krebs cycle.

Lactate threshold an intensity above which the production of lactate will increase sharply.

Lipase an enzyme responsible for breakdown of triglycerides and found in the liver, adipose tissue, muscle, as well as blood vessels.

Malonyl-CoA an intermediate in fatty acid synthesis that regulates fat utilization.

Nitrogen balance a measure that assesses the relationship between the dietary intake of protein and protein that is degraded and excreted.

Phosphofructokinase a rate-limiting enzyme that regulates glycolysis.

Somatomedins a group of hormones that promote cell growth and division.

Transcription a process that involves copying or transcribing the DNA's code from the gene into a molecule of messenger RNA.

Translation a process in which transfer RNA or tRNA reads the code and delivers the needed amino acids to form a polypeptide chain.

10 Guidelines for designing a healthy and competitive diet

Contents

Key terms

- Acceptable macronutrient distribution
- Adequate intake levels
- Daily value
- Adequacy
- Balance
- *Dietary Guidelines for Americans*

- Dietary Reference Intakes
- Essential nutrients
- Estimated energy requirements
- Glycogen supercompensation
- Moderation
- Nutrient content claims
- Recommended dietary allowances
- Variety
- Discretionary calories
- Estimated average requirements
- Female athlete triad
- Health claims
- Nonessential nutrients
- Nutrient density
- Tolerable upper intake levels

Healthful nutrition for fitness and sport

As noted in previous chapters, six classes of nutrients are considered necessary in human nutrition: carbohydrates, lipids, proteins, vitamins, minerals, and water. Within most of these general classes (notably proteins, vitamins, and minerals) are a number of specific nutrients necessary to sustain life. These nutrients are collectively considered as **essential nutrients**. In nutrition, essential nutrients are those that the body needs but cannot produce at all or cannot produce in adequate quantities. For example, we must obtain essential amino acids from food we eat regularly in order to synthesize the proteins we need. About 40 nutrients are currently known to be essential for human beings. **Nonessential nutrients** are ones the body can make in sufficient amounts when they are needed. Most foods contain a mixture of essential and nonessential nutrients.

There are a set of dietary principles that must followed in order to maintain a sufficient intake of essential nutrients. These principles include *variety, balance, and moderation*. **Variety** emphasizes the importance of choosing foods from a variety of food sources to create a diet that contains sufficient amounts of all the required nutrients. A variety of foods is best because no one food meets all your nutrient needs. For example, meats provide protein and iron, but litter calcium and no vitamin C, and milk contains calcium but very little iron. A diverse diet also makes mealtimes more interesting. Eating nutritious meals need never be boring.

Balance, also referred to as proportionality, involves consuming enough, but not too much, of each type of food. For example, meats, fish, and iron are rich in iron but poor in calcium. Conversely, milk and milk products are rich in calcium but poor in iron. Therefore, one should use a balanced approach; that is, to consume some meats and some milk products in order to obtain both essential minerals, and to also save some space for other foods, such as grains, vegetables, and fruits, since a diet consisting of meat and milk alone would not be adequate. Balance also refers to matching energy intake (calories consumed) with energy expenditure (calories burned) over time. A sustained imbalance between energy intake and energy expenditure can lead to fluctuations in body weight.

Moderation, or not consuming too much of a particular food, is also important, especially when it comes to controlling caloric intake and maintaining a healthy body weight. For example, foods rich in fat and sugar provide enjoyment and energy but relatively few nutrients. They promote weight gain when eaten in excess. A person practicing moderation would eat such foods only on occasion and would regularly select foods low in fat and sugar. This practice also improves nutrient density. **Nutrient density** is defined as the amount of nutrients that are in a food relative to its energy content. Foods with high nutrient densities or nutrient-dense foods provide high amounts of essential nutrients relative to the amount of calories. Eating in moderation requires paying attention to portion size and to choose foods that contains adequate essential nutrients in conjunction with reasonably low calories. Foods that are notably low in nutrient density, such as potato chips, candies, and colas, are sometimes referred to as empty calorie foods in that they deliver only energy with little or no essential nutrients.

Nutrition recommendations around the world

The earliest nutrition recommendations can be traced back to the late eighteenth century when the Industrial Revolution in England caused a rise in urban populations with large numbers of homeless people. Such an issue of poverty prompted the government to launch their quest to explore ways of keeping these people alive and maintaining the workforce. As a result, a dietary standard was established on what the average working individual ate in a typical day. This method of estimating nutrient needs was used until World War I when the British Royal Society made specific recommendations about foods that would not only sustain life but would also protect health. Based on the evidence that several diseases associated with the consumption of poor diets were caused by nutritional deficiencies, a food committee of the British Royal Society, besides recommending 70 to 80 grams of protein and 3000 kilocalories of food energy for the "average man," stated that every diet should include a certain proportion of fresh fruits and green vegetables, and that diets of all children should contain a considerable proportion of milk (Leitch 1942). Since then, the governments of many countries have established their own sets of dietary recommendations based on nutritional problems and dietary patterns specific to their populations and interpretations of their scientists. In general, the differences between guidelines from country to country are small and they all reflect the dietary principles of variety, balance, and moderation. The following are brief descriptions of dietary standards adopted by selected countries.

The United Kingdom

The United Kingdom published its first set of dietary guidelines in 1994, and they have been regularly updated since then. The national food guide, then known as "The balance of good health," was launched in 1994. It was revised and named "The eatwell plate" in 2007 and the most recent model, *The Eatwell Guide*, was published in March 2016. *The Eatwell Guide* has been accepted across government departments and by Food Standards Scotland, the Welsh Government, and by the Food Standards Agency in Northern Ireland. The guidelines are directed at the general population from the age of 2. It is recommended that children between the ages of 2 and 5 should start moving toward the diet depicted in *The Eatwell Guide*.

The Eatwell Guide is the key nutrition policy tool for health professionals and others working to improve dietary health. It is supported by eight tips for eating well: (1) Base your meals on starchy foods. (2) Eat lots of fruit and vegetables. (3) Eat more fish – including a portion of oily fish each week. (4) Cut down on saturated fat and sugar. (5) Eat less salt – no more than 6g a day for adults. (6) Get active and maintain a healthy weight. (7) Don't get thirsty. (8) Don't skip breakfast. *The Eatwell Guide* is a visual representation of how different foods contribute toward a varied and nutritious diet. It is based on five food groups and shows the proportion that each food group should contribute to a healthy balanced diet. Specifically, *The Eatwell Guide* suggests the following:

- Eat at least five portions of a variety of fruit and vegetables every day.
- Base meals on potatoes, bread, rice, pasta, or other starchy carbohydrates; choosing wholegrain versions where possible.
- Have some dairy or dairy alternatives (such as soya drinks); choose lower fat and lower sugar options.
- Eat some beans, pulses, fish, eggs, meat, and other proteins (including two portions of fish every week, one of which should be oily).
- Choose unsaturated oils and spreads, and eat in small amounts.

- Drink six to eight cups/glasses of fluid a day.
- If consuming foods and drinks high in fat, salt, or sugar, have these less often and in small amounts.

Australia

The National Health and Medical Research Council released the new Australian dietary guidelines in February 2013. This is the fourth edition of dietary guidelines in Australia (first edition 1982, second edition 1992, third edition 2003). The review process of the Australian dietary guidelines was led by a committee of the National Health and Medical Research Council and leading experts in the field of nutrition, public health, industry, and consumer issues. This revision was also jointly partnered with and funded by the Commonwealth Department of Health. The guidelines are based on the best available scientific evidence. The Department of Health has ongoing responsibility for implementing the guidelines. The Australian dietary guidelines are aimed at the healthy population aged over 2.

The document includes specific information for population subgroups such as pregnant women, children, or older adults where there are significant differences in nutritional requirements when compared to the general population. Australia uses a guide to healthy eating that visually represents on a plate the proportion of the five food groups for recommended consumption each day. The food groups included on the plate are: grain cereal foods; vegetables and legumes/beans; fruits; lean meats and poultry, fish, eggs, tofu, nuts, and seeds; reduced fat dairy products and/or alternatives. Outside of the plate there is the advice to drink plenty of water, and the recommendation to use oils in small amounts. Alcohol and highly processed foods (high in sugar, fat, and sodium) should be consumed only sometimes and in small amounts. The guidelines include five core recommendations which aim to direct people to the types and amounts of foods they should consume:

- To achieve and maintain a healthy weight, be physically active, and choose amounts of nutritious food and drinks to meet energy needs.
- Enjoy a wide variety of nutritious foods from these five groups every day:
    - plenty of vegetables, including different types and colors, and legumes/beans
    - fruit
    - grain (cereal) foods, mostly wholegrain and/or high cereal fiber varieties, such as breads, cereals, rice, pasta, noodles, polenta, couscous, oats, quinoa, and barley
    - lean meats and poultry, fish, eggs, tofu, nuts and seeds, and legumes/beans
    - milk, yoghurt, cheese, and/or their alternatives, mostly reduced fat (reduced fat milks are not suitable for children under the age of 2).
- Drink plenty of water.
- Limit intake of foods containing saturated fat, added salt, added sugars, and alcohol.
- Encourage, support, and promote breastfeeding.
- Care for your food; prepare and store it safely.

Canada

The first set of Canadian dietary guidelines was published in 1942 and they have been regularly updated since then. The current version of *Eating Well* with Canada's Food Guide was published in 2007. The Federal Ministry of Health (Health Canada) is

responsible for developing national dietary guidelines in consultation with Canadians from coast to coast, including non-governmental organizations, academics, health professionals, government, industry, and consumers. To develop the 2007 version of the guidelines Health Canada worked closely with three advisory groups: an external Food Guide Advisory Committee, an Interdepartmental Working Group, and the Expert Advisory Committee on Dietary Reference Intakes. The messages of the guidelines are aimed at the general population aged 2 and older.

Canada's Food Guide is illustrated using an image of a rainbow. The rainbow graphic displays the four food groups with examples of nutritious foods in each of the groups. It includes recommendations for the quantity of food to eat for different age and sex groups and directional statements for each food group to guide the quality of food choices. Other messaging addresses advice for specific life stages, added fats and oils, foods and beverages to limit, water, the importance of variety, physical activity, and nutrition labeling. The following are the more specific messages conveyed from the guidelines:

- Eat at least one dark green and one orange vegetable each day.
    - Go for dark-green vegetables such as broccoli, romaine lettuce, and spinach.
    - Go for orange vegetables such as carrots, sweet potatoes, and winter squash.
- Enjoy vegetables and fruit prepared with little or no added fat, sugar or salt.
    - Have vegetables steamed, baked or stir fried instead of deep fried.
    - Have vegetables and fruit more often than juice.
- Make at least half of your grain products wholegrain each day.
    - Eat a variety of wholegrains such as barley, brown rice, oats, quinoa, and wild rice.
    - Enjoy wholegrain breads, oatmeal, or wholewheat pasta.
- Choose grain products that are low in fat, sugar, or salt.
    - Compare the Nutrition Facts table on labels to make wise choices.
    - Enjoy the true taste of grain products; when adding sauces or spreads use small amounts.
- Drink skim, 1 percent or 2 percent milk each day.
    - Drink 500 ml (2 cups) of milk every day for adequate vitamin D.
    - Drink fortified soy beverages if you do not drink milk.
- Select lower fat milk alternatives.
    - Compare the Nutrition Facts table on yogurts or cheeses to make wise choices.
    - Have meat alternatives such as beans, lentils, and tofu often.
- Eat at least two food guide servings of fish each week. Health Canada provides advice for limiting exposure to mercury from certain types of fish.
    - Choose fish such as char, herring, mackerel, salmon, sardines, and trout.
- Select lean meat and alternatives prepared with little or no added fat or salt.
    - Trim the visible fat from meats; remove the skin from poultry.
    - Use cooking methods such as roasting, baking, or poaching that require little or no added fat.
    - If you eat luncheon meats, sausages, or prepackaged meats, choose those lower in salt (sodium) and fat.

- Enjoy a variety of foods from the four food groups.
- Satisfy thirst with water!
- Drink water regularly. It's a calorie-free way to quench your thirst. Drink more water in hot weather or when you are very active.
- Include a small amount (30 to 45 ml, 2 to 3 tbsp) of unsaturated fat each day. This includes oil used for cooking, salad dressings, margarine, and mayonnaise.
    - Use vegetable oils such as canola, olive, and soybean.
    - Choose soft margarines that are low in saturated and trans fats.
    - Limit butter, hard margarine, lard, and shortening.

The United States

The United States published the eighth edition of its *Dietary Guidelines for Americans* in January 2016. The *Dietary Guidelines for Americans* is jointly issued every five years by the U.S. Department of Health and Human Services (HHS) and the U.S. Department of Agriculture (USDA). The guidelines are developed through a process that has become increasingly more robust and transparent with each edition. The process to update the *Dietary Guidelines* occurs in two stages: (1) reviewing the current scientific evidence by an Advisory Committee consisting of prestigious researchers and scientists in the fields of nutrition, health, and medicine; and (2) developing the *Dietary Guidelines for Americans* by a group of experts from both HHS and USDA who have extensive knowledge of nutrition and health science, federal nutrition recommendations, and program implementation. Recommendations from the *Dietary Guidelines* are intended for Americans aged 2 and older, including those at increased risk of chronic disease. The focus of the *Dietary Guidelines* is disease prevention – they are not intended to treat disease.

The 2015 to 2020 *Dietary Guidelines for Americans* provides five overarching guidelines that encourage healthy eating patterns:

- Follow a healthy eating pattern across the life span. All food and beverage choices matter. Choose a healthy eating pattern at an appropriate calorie level to help achieve and maintain a healthy body weight, support nutrient adequacy, and reduce the risk of chronic disease.
- Focus on variety, nutrient density, and amount. To meet nutrient needs within calorie limits, choose a variety of nutrient-dense foods across and within all food groups in recommended amounts.
- Limit calories from added sugars and saturated fats and reduce sodium intake. Follow an eating pattern low in added sugars, saturated fats, and sodium. Cut back on foods and beverages higher in these components to amounts that fit within healthy eating patterns.
- Shift to healthier food and beverage choices. Choose nutrient-dense foods and beverages across and within all food groups in place of less healthy choices. Consider cultural and personal preferences to make these shifts easier to accomplish and maintain.
- Support healthy eating patterns for all. Everyone has a role in helping to create and support healthy eating patterns in multiple settings nationwide, from home to school to work to communities.

A healthy eating pattern includes the following:

- A variety of vegetables from all of the subgroups: dark green, red and orange, legumes (beans and peas), starchy, and others.

- Fruits, especially whole fruits.
- Grains, at least half of which are wholegrains.
- Fat-free or low-fat dairy, including milk, yogurt, cheese, and/or fortified soy beverages.
- A variety of protein foods, including seafood, lean meats and poultry, eggs, legumes (beans and peas), and nuts, seeds, and soy products.
- Oils.

Using dietary reference standards for constructing a diet

It is not enough to simply know how much nutrients and energy a person consumes; a complete assessment of one's nutritional status must go one step further and determine whether these amounts are likely to be adequate. For this purpose, the Institute of Medicine of the National Academy of Science has developed a set of nutritional standards to be used for assessing the adequacy of a person's diet. These standards are collectively called the **Dietary Reference Intakes** (DRIs). These standards were first published in 1943, when malnutrition in the United States was generally due to under-nutrition, and nutrition deficiencies were common. DRIs were established by highly qualified scientists and represent our best knowledge of recommended intake for all the essential nutrients. Because nutrient requirements differ by sex, age, and life stage, such as pregnancy and lactation, DRI values are stratified by each of these variables. Both the United States and Canada recognize the DRIs as their official set of dietary reference standards.

Dietary reference standards

The DRIs represent a set of four types of nutrient intake reference standards used to assess and plan dietary intake. They include: (1) **Estimated Average Requirements** (EARs); (2) **Recommended Dietary Allowances** (RDAs); (3) **Adequate Intake Levels** (AIs), and (4) **Tolerable Upper Intake Levels** (ULs). The DRIs also include calculations for **Estimated Energy Requirements** (EERs), which may be used to assess whether one's energy intake is sufficient, and **Acceptable Macronutrient Distribution** (AMDRs), which provide a recommended distribution of macronutrients in terms of energy consumption. Note that DRIs are only estimates of average nutrient requirements in a healthy population, so your level may be lesser or greater than the average. DRIs are provided in Appendix C. The following is a brief description of each of these specific types of nutrient intake reference standards.

Estimated Average Requirement (EARs)

The EAR for a particular nutrient is the average daily amount that will maintain a specific biochemical or physiological function in half of the healthy people of a given age and gender group. In other words, if a woman consumes the EAR value for a particular nutrient, she is consuming the amount that meets the requirement of about 50 percent of the all women in the same age group. A look at enough individuals reveals that their requirements fill a symmetrical and normal distribution, with most near the midpoint or the mean (as shown in Figure 10.1) and only a few at the extremes.

The EARs are useful in research settings to evaluate whether a group of people are likely to be consuming adequate amounts of a nutrient. However, it may not be appropriate to use the EARs as recommended dietary intake goals for a specific individual. This is because even though the EARs are differentiated by age and gender, the exact requirements of people of the same age and gender are likely to be different.

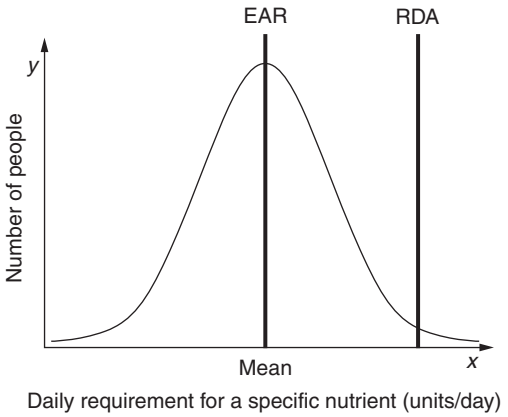


Figure 10.1 Comparison of estimated average requirements (EARs) and recommended dietary allowances (RDAs)

Recommended Dietary Allowance (RDA)

The RDA represents the average daily amount of a nutrient considered adequate to meet the known nutrient needs of nearly all healthy people of a given age and gender group. If people were to follow the EARs and consumed exactly the average requirement of a given nutrient, half of the population would develop deficiencies of that nutrient. Recommendations should be set high enough above the EARs to meet the needs of most healthy people. Small amounts above the daily requirement do no harm, whereas amounts below the requirement lead to health problems. Therefore, to ensure that the nutrient RDA meets the needs of as many people as possible, the RDAs are set near the top end of the range of the population's estimated requirements.

Referring to Figure 10.1, an RDA is set near the right end of the curve. Such a point can be calculated mathematically so that it covers ~98 percent of a population. Almost everyone, including those whose needs are higher than the average, will be included if they meet this dietary goal. In this context, RDAs have been used as nutrient intake goals for all individuals. They include a built-in safety margin to help assure adequate nutrient intake in the population. Unless specifically noted, RDAs do not distinguish between whether the nutrient is found in foods, added to foods, or consumed in supplement form.

Adequate Intake level (AI)

AI is the average daily amount of a nutrient that appears sufficient to maintain a specific criterion. It was a value used as a guide for nutrient intake when scientific evidence was insufficient to establish an EAR and thus to accurately set an RDA. In other words, the establishment of an AI instead of an RDA for a nutrient means that more research is needed. Similar to RDAs, AIs are meant to be used as nutrient intake goals for individuals. However, their differences are noteworthy. An RDA for a given nutrient is supported by enough scientific evidence to expect that the needs of almost all healthy people will be met. An AI, on the other hand, is determined based primarily on scientific judgments because sufficient scientific evidence is lacking. The percentage of people covered by an AI is unknown; an AI is expected to exceed average requirements, but it may cover more or fewer people than an RDA would if an RDA could be determined.

An example of a nutrient with an AI instead of an RDA is calcium. More research is required to be able to establish RDAs for this mineral. You can see which nutrients have AI versus RDA values by examining the DRI tables in Appendix C.

Tolerable Upper Intake Levels (ULs)

The RDA and AI values have been established to prevent deficiencies and decrease risk of chronic diseases. However, avoiding the other end of the nutritional status continuum – nutrient overconsumption or toxicity – is also important. As such, ULs have been established as the maximum daily amount of a nutrient that appears safe for most healthy people and beyond which there is an increased risk of adverse health effects. ULs are not to be used as target intake levels or goals. Instead, they provide limits for those who take supplements or consume large amounts of fortified foods because some nutrients are harmful at very high intakes. Note that scientific data are insufficient to provide UL values for all nutrients. The lack of ULs for a particular nutrient indicates the need for caution in consuming high intakes of that nutrient; it does not mean that high intakes pose no risk.

Estimated Energy Requirements (EERs)

EERs represent the average energy intakes needed to maintain weight in a healthy person of a particular age, sex, weight, height, and physical activity level. EERs are similar to EARs in that they are set at the average of the population's estimated requirements (Figure 10.2). In contrast to the RDA and AI values for nutrients, the recommendation for energy is not generous. Balance is the key to the energy recommendation. Enough energy is needed to sustain a healthy and active life, but too much energy can result in weight gain and obesity. Because any amount in excess of needs results in weight gain, there are neither RDAs nor ULs for energy.

The EER equations for adults of a healthy weight are provided as follows, and others may be found in Appendix D.

$$\text{Adult man: EER} = 662 - [9.53 \times \text{age (y)}] + \text{PA} \times [15.91 \times \text{wt (kg)} + 539.6 \times \text{Ht (m)}]$$

$$\text{Adult woman: EER} = 354 - [6.91 \times \text{age (y)}] + \text{PA} \times [9.36 \times \text{wt (kg)} + 726 \times \text{Ht (m)}]$$

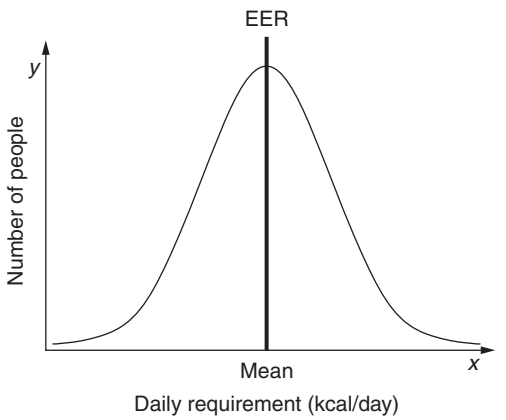


Figure 10.2 Estimated energy requirement (EER). Note the similarity between EER and EAR shown in Figure 10.1

In this equation, PA refers to physical activity level, which is categorized as sedentary, low active, active, or very active. Table 10.1 shows examples of these activity categories and their corresponding values. The following is a sample calculation for determining an EER:

> John Doe is a 35-year-old man who weighs 154 pounds, is 5 feet 9 inches tall, and has a low activity level, which is equal to 1.12 according to Table 10.1. His EER is calculated as follows:
>
> Age = 35 years
> Physical activity (PA) = 1.11
> Weight (wt) = 154 pounds = 70 kg (154 + 2.2)
> Height (Ht) = 5'9" = 69" = 1.75 m (69 × 0.0254)
>
> $$\begin{aligned}\text{EER} &= 662 - [9.53 \times \text{age (y)}] + \text{PA} \times [15.91 \times \text{wt (kg)} + 539.6 \times \text{Ht (m)}] \\ &= 662 - [9.53 \times 35] + 1.11 \times [15.91 \times 70 + 539.6 \times 1.75] \\ &= 662 - 333.55 + 1.11 \times [1113.7 + 944.3] = 662 - 333.55 + 2284.38 = 2613 \text{ kcal/day}\end{aligned}$$

Acceptable Macronutrient Distribution Ranges (AMDRs)

People don't eat energy directly; they derive energy from energy-containing nutrients such as carbohydrates, lipids, and proteins. Each of these nutrients contributes to the total energy intake, and those contributions vary in relation to each other. The AMDRs reflect the ranges of intakes for each class of energy source that are associated with reduced risk of chronic disease while providing adequate intakes of essential nutrients. The AMDRs, which are expressed as percentages of total energy intake, are listed below and may be found in Appendix C:

- Carbohydrate: 45 to 65 percent of total energy.
- Protein: 10 to 35 percent of total energy.
- Lipids: 20 to 35 percent of total energy.

To meet daily energy and nutrient needs while minimizing risks for developing chronic diseases such as heart disease and type 2 diabetes, an average adult should consume between 45 and 65 percent of total calories from carbohydrates. This relatively wide

Table 10.1 Physical activity (PA) categories and values

Activity level of category	*Physical activity value*		*Major action*
	Men	*Women*	
Sedentary	1.00	1.00	No physical activity aside from that needed for independent living
Low active	1.11	1.12	1.5–3 miles/day at 2–4 miles/hour in addition to the light activity associated with typical day-to-day life
Active	1.25	1.27	3–10 miles/day at 2–4 miles/hour in addition to the light activity associated with typical day-to-day life
Very active	1.48	1.45	10 more miles/day at 2–4 miles/hour in addition to the light activity associated with typical day-to-day life

range provides for flexibility, in recognition that both the high-carbohydrate/low-fat diet of Asian peoples and the relatively high-fat diet of people from the Mediterranean region with its high monounsaturated fatty acid olive oil content, contribute to good health. Acceptable lipid intake ranges between 20 and 35 percent of caloric intake. This range is consistent with the 30 percent limit set by the American Heart Association, the American Cancer Society, and National Institutes of Health. It is believed that very low fat intake combined with high intake of carbohydrate tends to lower HDL-cholesterol and raise triglyceride levels. On the other hand, high intake of dietary fat coupled with increased total caloric intake contributes to obesity and its related medical complications. Moreover, high-fat diets are usually associated with an increase in saturated fatty acid intake and LDL-cholesterol, which further potentiates coronary heart disease risk. Recommended protein intake ranges between 10 and 30 percent of total calories, and this range is broad enough to cover the protein needs of all individuals regardless of their age, gender, and training status.

The DRIs have many uses. They provide a set of standards that may be used to plan diets, to assess the adequacy of diets, and to make judgments about deficient or excessive intakes for individuals and populations. For example, they may be used as a standard for meals prepared for schools, for hospitals, and for government feeding programs for the elderly. They may be used to determine standards for food labeling and to develop practical tools for diet planning. They may also be used to evaluate the nutritional adequacy of the foods consumed by an individual or population that may be of health concern. Each of the DRI categories serves a unique purpose. For example, the EARs are most appropriately used to develop and evaluate nutrition programs for groups such as schoolchildren. The RDAs or AIs (if an RDA is not available) may be used to set goals for individuals. The ULs help guard against the overconsumption of nutrients and to keep nutrient intakes below the amounts that increase the risk of toxicity.

Planning a nutritious diet using MyPyramid

The first publication with regard to the official dietary guidelines can be traced back to more a century ago when the U.S. Department of Agriculture (USDA), which works both to optimize the nation's agricultural productivity and to promote a nutritious diet, published its first set of nutritional recommendations for Americans. Since this publication there have been a succession of versions, all designed to translate nutrient intake recommendations into guidelines for dietary planning. In 1980, the USDA and the U.S. Department of Health and Human Services (DHHS) jointly issued a new form of dietary recommendations called ***Dietary Guidelines for Americans***, which provided specific advice about how good dietary habits can promote health and reduce the risk for major chronic disease. These guidelines were revised about every five years, and the latest version was published in 2015 and was accompanied by an updated version of the federal food guide system called MyPyramid aimed to help people put the recommendations of the dietary guidelines into practice.

Dietary Guidelines for Americans

The 2015 *Dietary Guidelines for Americans* identify 41 key recommendations, of which 23 are for the general public and 18 are for special populations. They are grouped into nine general topics:

- Adequate nutrient intake within calorie needs.
- Weight management.

- Physical activity.
- Specific food groups to encourage.
- Fats.
- Carbohydrates.
- Sodium and potassium.
- Alcoholic beverages.
- Food safety.

The 2015 *Dietary Guidelines for Americans* are available at www.healthierus.gov/dietary guidelines. In general the dietary guidelines recommend that we:

- Consume a variety of nutrient-dense foods and beverages within and among the basic food groups identified in the new version of the food guide pyramid, while choosing foods that limit the intake of saturated and trans fats, cholesterol, added sugars, salt, and alcohol (if used). Foods to emphasize are vegetables, fruits, legumes, wholegrains, and fat-free or low-fat milk or equivalent milk products.
- Maintain body weight in a healthy range by balancing calorie intake from foods and beverages with calories expended. For the latter, engage in at least 30 minutes of moderate-intensity physical activity, above usual activity, at work or home on most days of the week.
- Practice food handling when preparing food. This includes cleaning hands, food contact surfaces, and fruits and vegetables before preparation and cooking foods to a safe temperature to kill micro-organisms.

To follow the Dietary Guidelines, one must keep in mind the five diet-planning principles: (1) adequacy, (2) balance, (3) nutrient density, (4) moderation, and (5) variety.

Adequacy means that diet provides sufficient energy and enough of all the nutrients to meet the needs of healthy people. For example, each day the body loses some iron, so people have to replace it by eating foods that contain iron. Otherwise, they may develop the symptoms of iron-deficient anemia such as feeling weak, tired, and having frequent headaches.

MyPyramid: a menu-planning tool

To help people put recommendations of the Dietary Guidelines into practice, the USDA has established its newest food guidance system called MyPyramid that replaces the USDA Food Guide Pyramid published in 1992 (www.mypyramid.gov). This most current version of MyPyramid is entitled "Steps to a Healthy You," which is reflected in the image of a person climbing the pyramid (Figure 10.3). It provides a more "individualized" approach to improving diet and lifestyle than previous guides. The MyPyramid symbol represents the recommended proportion of foods from each food group to create a healthy diet. Physical activity is a new element in the pyramid. It sends a clear message that consumers should choose the right amounts and types of food to balance their daily physical activity.

Several key elements of the MyPyramid symbol are worth noting. As mentioned earlier, physical activity is emphasized. Balancing energy intake with energy expenditure is a major component of MyPyramid. Six of the food groups, namely grains, vegetables, fruits, oils, dairy products, and meats and beans, are represented in different colors, each with different widths on the MyPyramid symbol. MyPyramid recommends that we choose foods in approximate proportion to the base widths of the bands. Moderate intake of solid fats and added sugars is represented by the narrowing of each food

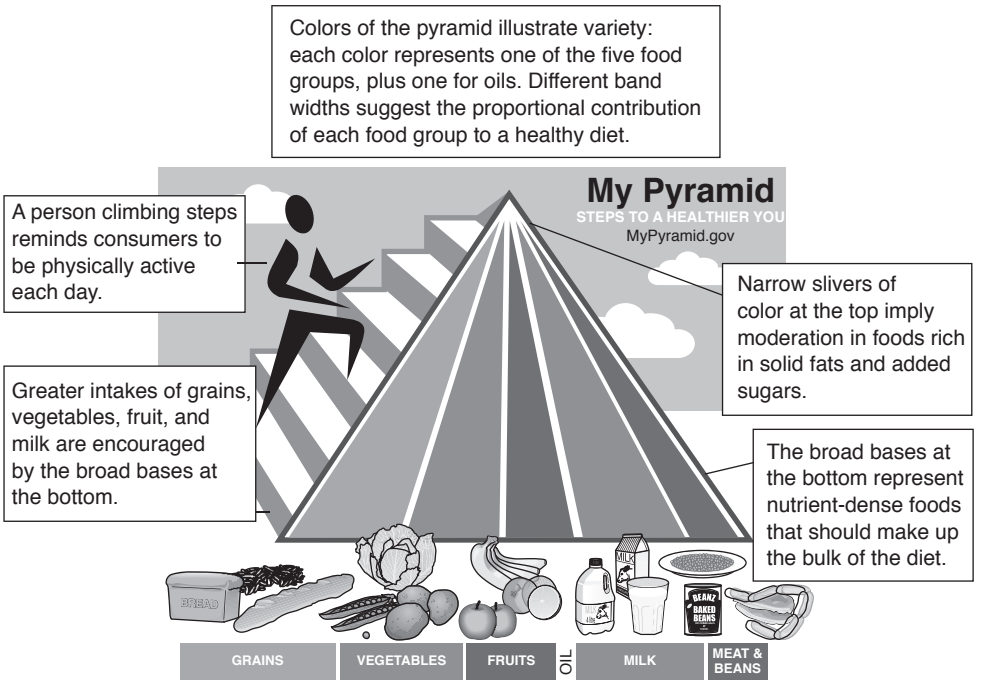


Figure 10.3 MyPyramid: Steps to a Healthier You

Source: USDA.

group's stripe from bottom to top. The narrowing pattern of the color bands from bottom to top also indicates that the more active you are, the more of these foods can fit into your diet.

To put MyPyramid into action, you need first to estimate your calorie needs using the method for determining EER. Once you have determined the calorie allowance appropriate for you, you can then use the data in Table 10.2 to discover how that calorie allowance corresponds to the recommended numbers of servings from each food group. Overall, MyPyramid translates the latest nutrition advice into 12 separate pyramids based on calorie needs (1000 to 3200 kcal).

Close attention should be paid to the stated serving size for each food group when following MyPyramid. This will help control the portion size and total caloric intake. The following are the commonly used household units that are equivalent to one serving size for each of the six food groups used by MyPyramid.

- Grains: 1 slice of bread, 1 cup of ready-to-eat breakfast cereal, or 1/2 cup of cooked rice, pasta, or cereal.
- Vegetables: 1 cup of raw or cooked vegetables or vegetable juice, or 2 cups of raw leafy greens.
- Fruits: 1 cup of fruit, 100 percent fruit juice, or 1/2 cup of dried fruit.
- Milks: 1 cup of milk or yogurt, 1.5 oz of natural cheese, or 2 oz of processed cheese.
- Meats and beans: 1 oz of meat, poultry, or fish, 1 egg, 1 tablespoon of peanut butter, 1/4 cup of cooked dry beans, or 1/2 oz of nuts or seeds.
- Oils: 1 teaspoon of any oil from plants or fish that is liquid at room temperature.

Table 10.2 MyPyramid recommendations or daily food consumption based on calorie needs

Calorie level	*1000*	*1200*	*1400*	*1600*	*1800*	*2000*	*2200*	*2400*	*2600*	*2800*	*3000*	*3200*
Fruits	1 cup	1 cup	1 1/2 cups	1 1/2 cups	1 1/2 cups	2 cups	2 cups	2 cups	2 cups	2 1/2 cups	2 1/2 cups	2 1/2 cups
Vegetables[1]	1 cup	1 1/2 cups	1 1/2 cups	2 cups	2 1/2 cups	2 1/2 cups	3 cups	3 cups	3 1/2 cups	3 1/2 cups	4 cups	4 cups
Grains[2]	3 oz	4 oz	5 oz	5 oz	6 oz	6 oz	7 oz	8 oz	9 oz	10 oz	10 oz	10 oz
Meats and beans	2 oz	3 oz	4 oz	5 oz	5 oz	5 1/2 oz	6 oz	6 1/2 oz	6 1/2 oz	7 oz	7 oz	7 oz
Milk[3]	2 cups	2 cups	2 cups	3 cups	3 cups	3 cups	3 cups	3 cups	3 cups	3 cups	3 cups	3 cups
Oils[4]	3 tsp	4 tsp	4 tsp	5 tsp	5 tsp	6 tsp	6 tsp	7 tsp	8 tsp	8 tsp	10 tsp	11 tsp

Notes
1 Vegetables are divided into five subgroups: dark green, orange, legumes, starchy, and other. A variety of vegetables should be eaten, especially green and orange vegetables.
2 At least half of the grain servings should be wholegrain varieties.
3 Most of the milk servings should be fat free or low fat.
4 Limit solid fats such as butter, stick margarine, shortening, and meat fat, as well as foods that contain these fats.

If interested, you may consider using the website at www.mypyramid.gov. This website provides the interactive technology that will allow consumers to obtain dietary recommendations specific to their age, gender, height, weight, and level of physical activity. It includes several important features: MyPyramid Menu Planner, Inside MyPyramid, MyPyramid Tracker, and MyFoodapedia. MyPyramid Menu Planner provides a brief estimate of what and how much food a person should eat from the different food groups based on each individual profile. Inside MyPyramid provides in-depth information for every food group, including recommended daily amounts in commonly used measures such as cups and ounces, with examples and everyday tips. The section also includes recommendations for choosing healthy oils, **discretionary calories**, and physical activity. The discretionary calories refer to the calories allowed from food choices rich in added sugars and solid fat. MyPyramid Tracker allows users to assess their diet quality and physical activity status by comparing a day's worth of foods eaten to the guidance provided by MyPyramid. Messages with regard to nutrition and physical activity are provided based on the need to maintain current weight or to lose weight. MyFoodapedia gives users quick access to searching for calories and MyPyramid food groups for a particular food. This section also allows comparison between any two foods.

Use of food labels in assisting dietary planning

Food labels are another tool that may be used in diet planning. They are designed to help consumers make healthy food choices by providing information about the nutrient composition of foods and about how a food fits into the overall diet. Today, nearly all foods sold in stores must be in a package that has a label containing the following information: (1) the product name, (2) name and address of the manufacturer, (3) amount of product in the package, (4) ingredients listed in descending order by weight, and (5) Nutrition Facts panel. Of special interest to many people is the Nutrition Facts panel, which is a required component of most food labels. Understanding how to read a food label is important in making healthy food choices.

Nutrition facts

The nutrition information section of the label is entitled "Nutrition Facts" (Figure 10.4). In this section, the serving size is listed in common household and metric measures, and is based on a standard list of serving sizes designed to be representative of the serving sizes which people choose. In other words, serving sizes on the Nutrition Facts panel must be consistent among similar foods. The use of standard serving sizes allows comparisons to be made easily among products. For example, comparing the energy content of different types of crackers is simplified because all packages list energy values for a standard serving size of about 30 grams and tell you the number of crackers per serving.

The serving size on the label is followed by the number of servings per container. The label must then list the total kilocalorie (or calorie on food labels), kilocalories from fat, total fat, saturated fat, cholesterol, sodium, total carbohydrates, dietary fiber, sugars, and proteins. The amounts of these nutrients are given per serving, and most are listed as a percentage of a standard called the **daily value**. The percentage of the daily value (% DV) is usually given for each nutrient per serving and is based on a 2000-kilocalorie diet. For example, if a food provides 10 percent of the daily value for dietary fiber, then the food provides 10 percent of the recommended daily intake for dietary fiber in a 2000-kilocalorie diet. Daily values may not be as applicable to those who require considerably more or less than 2000 kilocalories per day. Daily dalues are mostly set at or close to the highest RDA value or related nutrient standard seen in the various age and gender categories for a specific nutrient (Appendix E).

Nutrition Facts

Serving Size 1 cookie (28g)
Serving Per Container 15

Amount Per Serving	
Calories 120	**Calories from Fat 45**
	% Daily Value*
Total Fat 5g	**8%**
Saturated Fat 3g	**15%**
Cholesterol 25mg	**8%**
Sodium 100mg	**4%**
Total Carbohydrate 18g	**6%**
Dietary Fiber less than 1 gram	**3%**
Sugars 11g	
Protein 1g	

Vitamin A 4%	•	**Vitamin C 0%**
Calcium 2%	•	**Iron 4%**

***Percent Daily Values are based on a 2,000 calorie diet. Your daily values may be higher or lower depending on your calorie needs**

	Calories:	2,000	2,500
Total Fat	**Less than**	**65g**	**80g**
Saturated Fat	**Less than**	**20g**	**25g**
Cholesterol	**Less than**	**300mg**	**300mg**
Sodium	**Less than**	**2,400mg**	**2,400mg**
Total Carbohydrate		**300g**	**375g**
Dietary Fiber		**25g**	**30g**

Calories per gram:
Fat 9 • Carbohydrate 4 • Protein 4

Figure 10.4 A sample Nutrition Facts panel

Many manufactures list the daily values set for dietary components such as fat, cholesterol, and carbohydrate on the Nutrition Facts panel. This can be useful as a reference point. As noted above, they are based on a 2000-kilocalorie diet; if the label is large enough, amounts based on 2500 kilocalories are listed as well for total fat, saturated fat, cholesterol, sodium, fiber, total carbohydrate, and dietary fiber. Daily values help consumers determine how a food fits into their overall diet.

Exceptions to food labeling

Foods such as raw fruits and vegetables, fish, meats, and poultry are currently not required to have a Nutrition Facts label. However, many grocers and some meat packers have voluntarily chosen to provide their customers with information about these products. Protein deficiency is not a public health concern in the United States. Therefore, disclosure of the percentage daily value for protein is not mandatory on foods for people over 4 years of age. If the percentage daily value for protein is given on a label, the Food and Drug Administration (FDA) requires that the product be analyzed for protein quality. This procedure is expensive and time-consuming, so many companies opt not to list a percentage daily value for protein. However, labels on food for infants and children under 4 years of age must include the percentage daily value for protein.

Nutrient content claims

Food labels may also contain additional nutrition-related information. For example, **Nutrient content claims** describe the level of a nutrient in a food. These include phrases such as "sugar free," "low sodium," and "good source of." The use of these terms is regulated by the FDA, and some of the approved definitions are provided as follows:

- Light or lite: If 50 percent or more of the calories are from fat, fat must be reduced by at least 50 percent as compared to a regular product. If less than 50 percent of calories are from fat, fat must be reduced by at least 50 percent or calories reduced by at least one-third compared to a regular product.
- Reduced calories: At least 25 percent fewer calories per serving compared to a regular product.
- Calorie free: Less than 5 calories per serving.
- Fat free: Less than 0.5 grams of fat per serving.
- Low fat: 3 grams of fat or less per serving.
- Saturated fat free: Less than 0.5 grams of saturated fat per serving.
- Low in saturated fat: 1 gram of saturated fat per serving and containing 15 percent or less of calories from saturated fat.
- Cholesterol free: Less than 2 milligrams of cholesterol per serving. Note that cholesterol claims are only allowed when food contains 2 grams or less of saturated fat per serving.
- Low in cholesterol: 20 milligrams of cholesterol or less per serving.
- Sodium free: Less than 5 milligrams of sodium per serving.
- Low in sodium: 140 milligrams of sodium per serving.
- Sugar free: Less than 0.5 grams of sugar per serving.
- High, rich in, or excellent source of: Contains 20 percent or more of the daily value to describe proteins, vitamins, minerals, dietary fiber, or potassium per serving.
- Fresh: A raw food that has not been frozen, heat processed, or otherwise preserved.
- Fresh frozen: Food was quickly frozen while still fresh.

Health claims

Food labels are also permitted to include a number of **health claims** if they are relevant to the product. The health claims refer to a relationship between a nutrient or a food and the risk of a disease or health-related condition. They may be used on conventional foods or dietary supplements, and can help consumers choose products that will meet their dietary needs or health goals. For example, low-fat milk, a good source of calcium, may include on the package label a statement indicating that a diet high in calcium will reduce the risk of osteoporosis. Health claims are permitted only after the scientific evidence is reviewed and found to be valid, and must be approved by the FDA. More complete information regarding nutrient claims and health claims may be found on the FDA website at www.fda.gov/Food/LabelingNutrition/default.htm. The claims allowed at this time may show a link between the following:

- A diet with sufficient calcium and a reduced risk of osteoporosis.
- A diet low in total fat and a reduced risk of some cancers.
- A diet low in saturated fat and cholesterol and a reduced risk of cardiovascular or heart disease.
- A diet rich in fiber and a reduced risk of some cancers.
- A diet low in sodium and high in potassium and a reduced risk of hypertension and stroke.

- A diet rich in fruits and vegetables and a reduced risk of some cancers.
- A diet adequate in the synthetic form of vitamin folate or folic acid and a reduced risk of neural tube defects.
- Use of sugarless gum and a reduced risk of tooth decay.
- A diet rich in fruits, vegetables, and grain products that contain fiber and a reduced risk of cardiovascular disease.
- A diet rich in wholegrain foods and other plant foods, as well as low in total fat, saturated fat, and cholesterol, and reduced risk of cardiovascular disease and certain cancers.
- A diet low in saturated fat and cholesterol that also includes 25 grams of soy protein and a reduced risk of cardiovascular disease.
- Fatty acids from oils present in fish and a reduced risk of cardiovascular disease.

Dietary considerations for physically active individuals and athletes

Adequate nutrition is essential to fitness and performance. For every exerciser, diet must provide sufficient energy from adequate sources to fuel activity, protein to maintain muscle mass, and water to transport nutrients and cool the body. In general, while there should be an increase in the total energy intake in order to meet the energy demands imposed by physical activity and training, research in sports nutrition indicates that those who exercise or train regularly to keep fit and competitive do not require additional nutrients beyond those obtained by consuming a nutritionally well-balanced diet. For example, the Dietary Guidelines suggest that one should maintain at least 50 percent of the total energy intake being derived from carbohydrates. This recommendation should apply to every physically active individual as well as to a majority of athletes. Remember: as the total caloric intake increases, the absolute quantity of carbohydrates consumed also increases despite the same proportion. However, modifications to the Dietary Guidelines may help enhance performance for certain athletic endeavors, especially those that challenge the body's limits.

Calorie needs

The amount of energy needed for an activity depends on not only the characteristics of the exerciser such as body size and body composition, but also the duration, intensity, and frequency of the activity (Table 10.3). A small person may need only 1800 kcal daily to sustain normal daily activities without losing body weight, while a large, muscular man may need 4000 kcal. For a casual exerciser, the energy needed for activity may increase energy expenditure by a few hundred kilocalories a day. However, for an endurance athlete, such as a marathon runner, the energy needed for training may increase expenditure by 2000 to 3000 kcal a day. Therefore, some athletes may need as much as 6000 kcal or more daily to maintain body weight while training. In general, the more intense the activity, the more energy it requires. For example, riding a bicycle involves less work than running the same distance and therefore requires less energy. Similarly, the more time spent exercising, the more energy it requires. Riding a bicycle for 60 minutes requires six times the energy needed to ride for 10 minutes. If an athlete experiences daily fatigue, the first consideration should be whether he or she is consuming enough food. Up to six meals per day may be needed, including one before each workout.

Body weight and composition can affect athletic performance. Athletes involved in activities where a small, light body offers an advantage, such as ballet, gymnastics, and

certain running events, may restrict energy intake to maintain a low body weight. While a slightly leaner physique may be beneficial, dieting to maintain an unrealistically low body weight can be harmful to health and performance. An athlete who needs to lose weight should do so in advance of the competitive season to prevent the restricted diet from affecting performance. In addition, to preserve lean body mass and enhance fat loss, weight loss should occur at a rate of 1 to 2 pounds per week. This can be accomplished by lowering food intake by 200 to 500 kilocalories per day while maintaining a

Table 10.3 Energy expenditure in kilocalories per hour based on body mass

Activity/sport	*50 kg*	*60 kg*	*70 kg*	*80 kg*	*90 kg*
Aerobic dance	270	310	350	380	420
American football	240	270	305	340	370
Aquarobics	235	290	310	360	400
Archery	190	220	250	270	300
Badminton	270	310	350	385	420
Baseball and softball	220	250	285	315	350
Basketball (half court)	240	270	305	340	370
Basketball (competition)	480	545	610	670	740
Body building	375	427	480	530	585
Bowling	215	230	275	305	335
Boxing (sparring)	190	220	250	270	300
Calisthenics	190	220	250	270	300
Canoeing and kayaking (4 mph)	240	270	350	385	420
Circuit training	263	300	335	375	410
Climbing (mountain)	480	545	610	680	745
Cricket (fielding)	240	270	350	385	420
Cross-country skiing	560	635	715	790	870
Cycling (moderate speed	165	190	214	240	260
Dance (social)	223	255	285	315	350
Fencing	240	270	305	340	370
Golf (walking with bag)	200	230	255	280	310
Gymnastics	255	280	315	350	380
Hockey	430	490	550	610	670
Horseriding	190	220	250	270	300
Ice hockey	280	270	355	395	435
Jogging (9 km/h)	520	590	660	735	806
Martial arts	250	280	315	350	385
Orienteering	520	590	660	735	806
Rope jumping (continuous)	560	635	715	790	870
Rowing (recreational)	190	220	250	270	300
Rugby	430	490	550	610	670
Running (16 km/h)	719	820	920	1016	1116
Skiing (downhill)	480	545	610	680	745
Soccer	430	490	550	610	670
Squash	480	545	610	680	745
Swimming (fast)	426	512	639	767	853
Swimming (slow)	349	419	524	629	698
Tennis	335	380	430	475	520
Table tennis	236	283	354	424	472
Volleyball	280	270	355	395	435
Walking (brisk)	240	280	315	350	385
Weight training	375	427	480	530	585

Source: adapted from *Food and Fitness: A Dictionary of Diet and Exercise, Oxford Food & Fitness Dictionary* (2003); McArdle *et al.* (2009).

regular exercise program. On the other hand, in sports such as American football and rugby, in which being large and heavy is advantageous, an increase in body weight may be desirable. If an athlete needs to gain weight, increasing food intake by 500 to 1000 extra calories per day should be consumed (Position of the American Dietetic Association, Dietitians of Canada, and the American College of Sports Medicine). In addition, strength training should accompany weight gain to promote an increase in lean body mass (Kraemer *et al.* 1999).

Carbohydrate, fat, and protein needs

The source of dietary energy is often as important as the amount of energy. In general, the diets of physically active individuals and most athletes should contain the same proportion of carbohydrate, fat, and protein as is recommended to the general public; that is, about 45 to 65 percent of total energy as carbohydrate, 20 to 35 percent of energy as fat, and 10 to 35 percent of energy as protein (Position of the American Dietetic Association, Dietitians of Canada, and the American College of Sports Medicine).

Carbohydrate needs

Carbohydrate represents the most important source of energy. Carbohydrate is needed to maintain blood glucose levels during exercise and to replace glycogen stores after exercise. In general, the diets of physically active individuals should contain the same proportion of carbohydrate, fat, and protein as recommended to the general public (mentioned above). However, athletes should be encouraged to aim at the high end of the percentage range for carbohydrate (i.e. ~60 percent). For a 2000 kcal diet, this translates into 300 g of carbohydrate (1 g of carbohydrate = 4 kcal) and 4.3 g per kg of body weight (if using a body weight of 70 kg). It is recommended that although the amount of carbohydrate needed depends on total energy expenditure, type of sport, gender, and environment, it should range from 6 to 10 grams per kilogram of body weight per day (Position of the American Dietetic Association, Dietitians of Canada, and the American College of Sports Medicine). People engaged in aerobic training and endurance activities lasting for about 60 minutes per day may need 6 to 7 grams per kilogram of body weight. When exercise duration approaches several hours per day, carbohydrate intake may increase up to 10 grams per kilogram of body weight. In other words, triathletes and marathoners should consider eating about 500 to 600 grams of carbohydrate daily, or even more if necessary, in order to prevent chronic fatigue and to load the muscles and liver with glycogen.

For athletes as well as physically active individuals, most of the carbohydrate in their diet should be complex carbohydrates from wholegrains and starchy vegetables, with some naturally occurring simple sugars from fruits and milk. These foods provide necessary vitamins, minerals, phytochemicals, and fibers as well as energy. Their focus is to include high-carbohydrate foods while moderating concentrated fat sources. Sports nutritionists emphasize the difference between a high-carbohydrate meal and a high-carbohydrate/high-fat meal. Before endurance events, such as marathons or triathlons, some athletes seek to increase their carbohydrate reserves by eating foods such as potato chips, French fries, and pastries. Although such foods provide carbohydrate, they also contain a lot of fat. Better carbohydrate choices include pasta, rice, potatoes, bread, fruit and fruit juices, and many breakfast cereals. Consuming a moderate rather than a high amount of fiber during the final day of training is a good precaution to reduce the chances of bloating and intestinal gas during the next day's event.

Fat needs

A diet containing up to 35 percent of calories from fat is generally recommended for athletes. Dietary fat supplies fat-soluble vitamins and essential fatty acids as well as an important source of energy. Body stores of fat provide enough energy to support the needs of even the longest endurance events. No performance benefits have been associated with diets containing less than 15 percent fat. On the other hand, excess dietary fat is unnecessary and excess energy consumed as fat, carbohydrate, and protein can cause an increase in body fat and thus weight gain. In addition, consumption of saturated fat and trans fat should be limited.

Protein needs

Protein is essential to maintain muscle mass and strength. The RDA for protein for non-athletes is 0.8 grams per kilogram of body weight. Therefore, a person weighing 70 kilograms requires 56 grams or 2 ounces of protein daily. Assuming that even during exercise, relatively little protein loss occurs through energy metabolism, this protein recommendation remains adequate for most active individuals.

Although a diet containing the RDA for protein (0.8 g/kg) provides adequate protein for most active individuals, competitive athletes participating in endurance and strength/power sports may require more protein. In endurance events such as marathons, protein is needed for energy and to maintain blood glucose, so these athletes may benefit from consuming 1.2 to 1.4 grams of protein per kilogram of body weight per day. Strength and power athletes who require amino acids to synthesize muscle proteins may benefit from 1.4 to 1.6 grams per kilogram of body weight per day. In fact, the protein intake for most athletes often exceeds the protein RDA, and their diet usually contains two to three times more protein than recommended values. For example, an 85-kilogram man who consumes 3000 kilocalories, 18 percent of which is from protein, his or her protein intake is 135 grams (1 gram of protein = 4 kilocalories) or 1.6 grams of protein per kilogram of body weight.

Any athlete not specifically on a low calorie regimen can easily meet the protein recommendations by eating a variety of foods. To illustrate, a 57-kg (125-lb) woman performing endurance activity can consume 68 g of protein (57 × 1.2) during a single day by including 3 oz of chicken (e.g., a chicken breast), 3 oz of beef (e.g., a small lean hamburger), and 2 glasses of milk in her diet. Similarly, a 77-kg (180-lb) man who wants to gain muscle mass through strength training needs to consume only 6 oz of chicken (e.g., a large chicken breast), 1/2 a cup of cooked beans, a 6-oz can of tuna, and 3 glasses of milk to achieve an intake of 125 g of protein (77 × 1.6) in a day. For both athletes, their calculations do not even include protein present in grains and vegetables which they will also eat. It is clear that by meeting calorie needs, many athletes consume much more protein than is required. There are hundreds of protein supplements that are commercially available. Although certain types of exercise do increase protein needs, the protein provided by these expensive supplements will not meet an athlete's needs any better than the protein found in a balanced diet.

Vitamin and mineral needs

Although vitamins and minerals are essential nutrients, the amount of vitamin we need to prevent deficiency is small. In general, humans require a total of about 1 oz (28 g) vitamins for every 70 kg (150 lb) of food consumed. Given such small requirements, with proper nutrition from a variety of food sources, the physically active person or

competitive athlete need not consume vitamin and mineral supplements. However, about 40 percent of adults in the United States take vitamin and/or mineral supplements on a regular basis, some at unsafe levels. They are spending $15 billion annually on supplements. The health-related value of this practice remains in debate.

Adequate vitamin and mineral intake is essential to optimal performance. In addition, the need for some micronutrients may be increased by exercise. Generally speaking, vitamin and mineral needs are the same or slightly higher for athletes compared with those of sedentary adults. However, athletes or physically active individuals usually have high caloric intakes, so they tend to consume plenty of vitamins and minerals. The only exceptions are that (1) they consume low-calorie diets, such as seen with female athletes participating in events in which maintaining a low body weight is crucial; (2) they are vegetarians who eliminate one or more food groups from their diet, and (3) they consume a large amount of processed foods and simple sugars with low nutrient density. In these adverse situations, a multivitamin and mineral supplement at recommended dosage can upgrade the nutrient density of the daily diet.

Vitamin needs

Of the many vitamins, B vitamins are among those that are often chosen as supplements because of the important roles they can play during exercise. Most B vitamins function as coenzymes and they are involved in energy production. They are also required for red blood cell synthesis, protein synthesis, and tissue repair and maintenance. Supplementing vitamins C and E is another common interest among athletes. Both serve as an antioxidant, and their deficiencies have been related to impaired synthesis of collagen, production of neurotransmitters, and anemia, all of which have high implications for exercise performance. However, no exercise benefit exists for vitamins with intakes above the recommended values. Supplementing for four days with a highly absorbed derivative of thiamin, a component of the pyruvate dehydrogenase that catalyzes the movement of pyruvate into the Krebs cycle, offered no advantage over a placebo on measures of oxygen uptake, lactate accumulation, and cycling performance during exhaustive exercise (Webster *et al.* 1997). In addition, studies using high-potency multivitamin-mineral supplementation for well-nourished, healthy individuals have failed to demonstrate any beneficial effect on aerobic fitness, muscular strength, and neuromuscular function following prolonged running or athletic performance (Gauche *et al.* 2006). The lack of efficacy of vitamin supplementation may be attributed to the fact that vitamin status in those who are physically active or highly trained athletes does not differ from that of untrained individuals, despite large differences in daily physical activity levels.

Given the important roles which vitamins play, any physically active individual or athlete should be cognizant of an adequate intake of these nutrients in order to maximize micronutrient density in their diet. The use of large doses of vitamins requires more study and is not currently recommended as an accepted part of dietary guidance for athletes. Experts suggest consuming a diet containing foods rich in B vitamins and antioxidants such as fruits, vegetables, wholegrain breads and cereals, and vegetable oils. There is evidence that antioxidant function in the body enhances as exercise training progresses. This would suggest that a physically active lifestyle coupled with a sound nutrition plan will be an ultimate solution to the success in fitness and performance. A multivitamin and mineral supplementation may be considered for athletes who restrict energy intake or use severe weight loss practices, eliminate one or more of the food groups, or consume high-carbohydrate and low-micronutrient-dense diets.

Mineral needs

The use of mineral supplements should not be recommended unless prescribed by a physician or registered dietician because of potential adverse consequences. A well-balanced diet with an adequate intake of total energy will provide more than enough of both major and minor minerals for all individuals. However, some minerals may be worth mentioning due to their greater loss pertaining to high-intensity training among athletes. For example, loss of water and accompanying mineral salts, primarily sodium, chloride, and potassium, in sweat pose an important challenge during prolonged exercise, especially during hot weather. Excessive water and electrolyte loss impairs heat tolerance and exercise performance, and may cause dysfunction in the form of heat cramps, heat exhaustion, and heat-stroke. The yearly number of heat-related deaths during summer football practice tragically illustrates the importance of fluid and electrolyte replacement. During a practice or game, an athlete may lose up to 5 kg (~10 lb) of water from sweating. This corresponds to a loss of about 8 g of salt because each kg (or liter) of sweat contains about 1.5 g of salt. Therefore, replacement of water and salt loss through sweat become the crucial and immediate needs. One can achieve proper supplementation by drinking a 0.1 to 0.2 percent salt solution (i.e., adding one-third of a teaspoon of table salt per liter of water). Further discussion on water and electrolyte loss and their replacement strategies is presented in Chapter 16.

Iron is involved in red blood cell production, oxygen transport, and energy production, so a deficiency of this mineral may detract from optimal athletic performance. For most individuals, exercise does not increase iron needs. However, in athletes, especially female athletes, a reduction in the amount of stored iron is common. Poor iron status may be caused by inadequate iron intake, increased iron needs, increased iron losses, or a redistribution of iron due to exercise training. Dietary iron intake may be limited in athletes who are attempting to keep body weight low, or in those who consume a vegetarian diet and therefore do not eat meat – an excellent source of readily absorbed iron. Iron needs may be increased in athletes because exercise stimulates the production of red blood cells, so more iron is needed for hemoglobin synthesis. Iron is also needed for the synthesis of muscle myoglobin and iron-containing proteins used for ATP production in mitochondria. An increase in iron loss with prolonged training, possibly because of increased urinary and sweat loss, also contributes to increased iron needs in athletes.

Calcium is another important mineral that deserves extra attention, particularly among women athletes who try to lose weight by restricting their intake of dairy products rich in calcium. Calcium is needed to maintain blood calcium levels and promote and maintain bone density, which in turn reduces the risk of osteoporosis. In general, exercise, especially weight-bearing exercise, increases bone density. However, in female athletes with extremely low body weight and body fat, their calcium status can be at risk. These athletes are found to also have a high risk for developing eating disorder and amenorrhea. The combination of disordered eating, amenorrhea, and osteoporosis is referred to as **female athlete triad**. Female athletes who strive to reduce their body weight to achieve an ideal body image and to meet the performance goals set by coaches, trainers, or parents are at increased risk for developing this syndrome of interrelated disorders. The extreme energy restriction that occurs in eating disorders can create a physiological condition similar to starvation and contribute to menstrual abnormalities. High intensities of exercise can also affect the menstrual cycle by increasing energy demands or by causing a decrease in female reductive hormones, particularly estrogen (Otis *et al.* 1997). When combined, energy restriction and excessive exercise can contribute to amenorrhea, the delayed onset of menstruation or the absence of three or more consecutive menstrual cycles. Loss of regular menstrual cycles in female athletes stems from a reduction of estrogen. A low level of estrogen has other

negative consequences for the body. It reduces calcium absorption and, when combined with poor calcium intake, leads to premature bone loss and increased stress fractures.

Female athletes experiencing symptoms of the female athlete triad, such as irregular menstrual periods and/or stress fracture, should consult a physician to determine the cause. Decreasing the amount of training or increasing energy intake and body weight often restore regular menstrual cycles and stabilize bone mass. A physician may prescribe multivitamin and mineral supplements as well as calcium supplements as needed to maintain an intake of at least 1200 milligrams per day. If irregular menstrual cycles persist, severe bone loss and osteoporosis can result. What is more alarming is that such bone loss cannot be completely reversed by either increasing dietary calcium or by performing more weight-bearing exercise. Therefore early prevention is crucial, and it is encouraged that teachers, coaches, health professionals, and parents educate female athletes about the triad and its health consequences.

Special planning for sports performance

For most of us, a trip to the gym requires no special dietary planning beyond that needed to consume a balanced diet as described above. However, for athletes competing in athletic events, foods eaten in preparation for a competition can mean the difference between victory and defeat. For this reason, specialized dietary advice has been developed with regard to what athletes should consume before, during, and after the competition or along with their regular training routines. For example, it has been considered that spaghetti, muffins, bagels, and pancakes with fresh fruits are good food choices for a pre-game meal. Liquid meal replacement formulas such as Carnation instant breakfast may also be used. Foods especially rich in fiber should be eaten the previous day to empty the colon before an event, but they should not be eaten the night before or in the morning before the event. For athletes involved in resistance training, consuming easily digestible protein in multiple and even doses has been recommended to maximize their anabolic adaptations. Experts have developed a number of sports nutrition recommendations, which will be discussed in the following sections.

Pre-competition meals

The pre-competition meal should provide adequate carbohydrate energy and ensure optimal hydration. As a general rule, the meal should be high in carbohydrate and low in fat and protein. High-fiber foods should be avoided to prevent feeling bloated during competitions. As increased stress and tension that usually accompany competitions decrease blood flow to the digestive tract, depressing intestinal absorption, the meal should be consumed three to four hours before the event. The amount of calories may vary depending on gender and size of the athlete, but it should be within a tolerable range, i.e., 300 to 500 kcal. This small intake of carbohydrate is to mainly optimize liver glycogen stores. As for food choices, athletes should select those that they prefer and/or believe that they will give them a winning edge. Some athletes find that in addition to a pre-competition meal, a small high-carbohydrate snack or beverage consumed shortly before an event may enhance performance (Coyle 1995). Because foods affect people differently, athletes should test the effects of their choices during training, not during competition. It must be emphasized that the importance of a pre-competition meal occurs only if the athlete maintains a nutritionally sound diet throughout training. Pre-competition meals cannot correct any existing nutritional deficiencies or inadequate nutrient intake in the weeks before competition. Table 10.4 exhibits sample pre-game meals that reflect this portion size and composition requirement.

Table 10.4 Sample pre- and post-exercise meals

Pre-exercise meals				*Post-exercise meals*			
	Food	*Serving*	*Calories and nutrients*		*Food*	*Serving*	*Calories and nutrients*
Option 1	Cheerios	3/4 cup	450 kcal	Option 1	Bagel	1	562 kcal
	Reduced-fat milk	1 cup	90 g (80%) carbohydrate		Peanut butter	2 tbsp	75 g carbohydrate
	Blueberry muffin	1			Fat-free milk	8 ounce	22 g protein
	Orange juice	4 ounces			Banana	1 med	
Option 2	Fruit yogurt	1 cup	482 kcal	Option 2	Instant breakfast	1 packet	438 kcal
	Bagel	half	85 g (70%) carbohydrate		Fat-free milk	8 ounces	70 g carbohydrate
	Apple juice	4 ounces			Banana	1 med	17 g protein
	Peanut butter	1 tbsp			Peanut butter	1 tbsp	

Glycogen supercompensation

While carbohydrate intake in the hours before a competition will mainly optimize liver glycogen, carbohydrate consumption in the days leading up to a competition allows muscle glycogen stores to be fully replenished. In 1967, Scandinavian scientists discovered that muscle glycogen could be supercompensated by changes in diet and exercise. In a series of studies, these scientists developed a so-called **glycogen supercompensation** or carbohydrate loading protocol, which has been found to be able to increase in muscle glycogen stores 20 to 40 percent above the level that would be achieved on a typical diet. This diet regimen involves depleting glycogen stores by exercising strenuously and then replenishing glycogen by consuming a high-carbohydrate diet for a few days before a competition, during which time only light exercise is performed. For example, consider the glycogen supercompensation schedule of a 25-year-old man preparing for a marathon. His typical calorie needs are about 3500 kcal per day. Six days before the competition, he completes a final hard workout of 60 minutes. On that day, carbohydrates contribute to 50 percent of his total caloric intake. As he goes through the rest of the week, the duration of his workout decreases to 40 minutes, and then to about 20 minutes by the end of the week. Meanwhile, he increases the amount (i.e., ~10 g kg^{-1}) of carbohydrate in his diet to reach at least 70 percent of the total caloric intake as the week continues. The total caloric intake should decrease as exercise time decreases. On the final day before the competition, he rests while maintaining the high-carbohydrate intake. The supercompensation regimen is illustrated in Table 10.5.

The regimen has been used successfully by several top endurance athletes (Sherman *et al.* 1981). In fact, many marathon runners still use this method to optimize their performance. Although the supercompensation protocol has been very effective in increasing muscle glycogen concentration, it also has several potential disadvantages of which athletes should be aware. During the first three days, athletes may experience hypoglycemia, and they may not recover very well from an exhausting exercise bout when insufficient carbohydrate is ingested. Some athletes also feel muscle stiffness while following the regimen. This is because an increase in muscle glycogen will require additional water to be incorporated into the muscle. In addition, as the protocol would require an athlete to reduce their training volume, most athletes won't feel comfortable and may develop mood disturbances which may have a negative effect on their mental preparation for an event.

The carbohydrate supercompensation regimen increased time to exhaustion on average by about 20 percent and reduced the time to complete a set task by 2 to 3 percent (Hawley *et al.* 1997). However, it seems that egogenic benefits of this protocol can only be demonstrated in events that last more than 90 minutes. Such carbohydrate loading appears to have no effect on sprint performance and high-intensity exercise of

Table 10.5 A modified regimen to supercompensate muscle glycogen stores

Days	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Exercise furation (min)	90	40	40	20	20	Rest	Competition
Exercise intensity (% VO_2max)	75	75	75	75	75	Rest	
Diet (% of calories from carbohydrate)	50% (4 g/kg)	50% (4 g/kg)	50% (4 g/kg)	70% (10 g/kg)	70% (10 g/kg)	70% (10 g/kg)	

up to about 30 minutes compared with normal diets (i.e., 50 percent carbohydrate). This finding is not unexpected, because for this exercise duration glycogen depletion is not a major performance-limiting factor. Carbohydrate supercompensation has also been reported to improve performance in team sports involving high-intensity intermittent bouts of exercise such as soccer and hockey (Balsom *et al.* 1999).

Carbohydrate supplementation during exercise

For sporting events that last longer than 60 minutes, carbohydrate feeding during exercise can also improve athletic performance. This is because prolonged exercise depletes muscle glycogen stores, and low levels of muscle glycogen and blood glucose lead to fatigue, both physical and mental. When endogenous carbohydrate stores, such as muscle glycogen, run low, athletes often complain of "hitting the wall," the point at which maintaining a competitive pace seems impossible. However, consuming about 60 grams of liquid or solid carbohydrate every hour has been shown to reverse this obstacle. It must be mentioned that such benefit of carbohydrate feeding has been generally demonstrated during exercise in which intensity exceeds 70 percent VO_2max. As mentioned in Chapter 4, sustained exercise at or below 60 percent VO_2max places much less demand on carbohydrate breakdown. This level of exercise does not tax glycogen reserves to a degree that would limit endurance. Nevertheless, glucose feedings provide supplementary carbohydrate during intense exercise when demand for glycogen increases significantly. The mechanisms by which carbohydrate feeding during exercise may improve endurance performance include the following:

- maintaining blood glucose and a high level of carbohydrate oxidation;
- sparing liver and possibly muscle glycogen;
- promoting glycogen synthesis, especially during low-intensity periods of intermittent exercise;
- enhancing the function of the central nervous system.

Studies have also addressed questions as to which carbohydrates are most effective, what is the most effective schedule, and what is the optimal amount of carbohydrate to consume. The timing of carbohydrate feedings seems to have little effect on the use of ingested carbohydrate, which is typically measured by determining exogenous carbohydrate oxidation rates. Studies in which a large dose (100 g) of carbohydrate in solution was given produced similar exogenous carbohydrate oxidation rates to studies in which 100 grams of carbohydrate were ingested at regular intervals. Knowing the amount of carbohydrate that needs to be ingested to attain optimal performance while producing no side effects is important. In theory, the optimal amount should be the amount that results in maximal exogenous carbohydrate oxidation rate. Through an analysis using a large number of studies, Jeukendrup and Jentjens (2000) found that carbohydrate feeding at rates of about 1 to 1.2 g/min produce the maximal exogenous carbohydrate oxidation rate. This finding suggests that athletes who adopt an ingestion rate of 60 to 70 g/hr can expect an optimal carbohydrate delivery. This amount of carbohydrate may be found in the following sources: 1 liter of sports drink (i.e., Gatorade, Powerade, Isostar), 600 ml of cola drink, 1.5 Power bars or Gatorade energy bars, or three medium bananas.

As far as the type of carbohydrate is concerned, results appear to be mixed. It appears that glucose is oxidized at much higher rates than fructose and galactose, because the latter would have to be converted into glucose in the liver before they can be metabolized. However, the oxidation rates of maltose, sucrose, and glucose polymers (maltodextrins) are comparable to those of glucose. In addition, starches

with a relatively large amount of amylopectin are rapidly digested and absorbed and their oxidation occurs at a similar rate as glucose, whereas those with high amylase content have a relatively slow rate of hydrolysis. A relatively newer view has now been offered toward a supplement that combines glucose and fructose. It is thought that the rate of exogenous carbohydrate oxidation is limited by intestinal absorption of carbohydrate rather than by gastric emptying or muscle glucose uptake (Jeukendrup 2004). When glucose and fructose are combined, intestinal carbohydrate absorption can be increased because the two monosaccharides are carried by different transporters. In a study that used trained cyclists, ingestion of glucose fed at a rate of 1.2 g min^{-1} and fructose at a rate of 0.6 g min^{-1} was found to be able to improve endurance performance by 8 percent compared with ingestion of glucose at a rate of 1.8 g min^{-1} (Currell and Jeukendrup 2008). Therefore, in order to maximize carbohydrate availability during exercise, one may choose to use glucose, maltose, sucrose, maltodextrins, or amylopectin as they can be digested, absorbed, and oxidized more rapidly, or consider using multiple transportable carbohydrate products that include glucose and fructose.

Dietary supplementation for recovery

Replenishing glycogen stores following exhaustive exercise is another important consideration. When exercise ends, the body must shift from the catabolic state of breaking down glycogen to the anabolic state of restoring glycogen, so that athletes can be ready for the next competition and training session. Often, the time to recover between successive athletic competitions or training sessions is very short. In such cases, rapid glycogen repletion becomes even more important. The timing of carbohydrate intake can have an important effect on the rate of muscle glycogen synthesis during recovery. In an early study, Ivy *et al.* (1988b) observed that when carbohydrate intake is delayed until two hours after exercise, the amount of muscle glycogen restored is only half of what was achieved when carbohydrate intake took place immediately following exercise. Glycogen synthesis is greatest immediately after exercise, because the muscles are insulin-sensitive at this point. It is also recommended that within this two-hour post-exercise period athletes should consume carbohydrate in an amount of 1.0 to 1.5 g per kg of body weight every hour (Ivy *et al.* 1988a).

Since timing is important, carbohydrate foods listed with a moderate to high glycemic index should be chosen to insure that more glucose molecules will be available in the blood immediately after exercise. Athletes can consume sugar candies, sugared soft drinks, fruit or fruit juice, or a sport-type carbohydrate supplement such as a sports bar or gel immediately after training. Later, they can choose enriched bread, mashed potatoes, and shortgrain white rice or spaghetti noodles. Recall that Table 2.4 shows the glycemic index and glycemic load for various foods. Because certain amino acids have a potent effect on the secretion of insulin, adding an appropriate amount of protein (i.e., in a ratio of 3 grams of carbohydrate to 1 gram of protein) during recovery can be especially helpful to maximize glycogen repletion. For a 70-kg athlete, this corresponds to about 75 g of carbohydrate and 25 g of protein. Table 10.4 exhibits sample post-exercise meals of this composition.

Intense training and competition lead to muscle fatigue and soreness as well as muscle structural damage, yet a proper supply of amino acids can augment protein synthesis and muscle repair. As such, supplementing protein or amino acids post exercise is another important recovery strategy, especially for those involved in resistance training. Research has suggested that providing an ample supply of amino acids for the muscles within one to three hours following exercise may help further stimulate protein synthesis

(Wolfe 2001). Gibala (2002) also indicated that consuming a drink containing 0.1 g of essential amino acids per kg body mass during first the first hours of recovery from heavy resistance would produce a more profound increase in protein synthesis. Such a dose (i.e., 7 g of essential amino acids for a 70-kg athlete) of essential amino acids is different when a complete protein is consumed. In a study that examined the impact of a protein dose on muscle protein synthesis following resistance exercise, Moore *et al.* (2009) observed a dose-dependent increase in protein synthesis. This study, however, also revealed that ingestion of 20 g of intact protein is sufficient to maximally stimulate protein synthesis. Just as with carbohydrate, the timing of taking protein or amino acids is important as well. The increased blood flow to the muscles during the immediate recovery period may permit a more effective delivery of the amino acids needed for protein synthesis. When supplementing protein post exercise, the use of a more easily absorbable protein, such as whey, is recommended. In a study involving a ten-week resistance training program, Cribb and Hayes (2006) found that consuming a supplement containing protein, creatine, and glucose immediately before and after training resulted in a greater increase in muscle mass and strength as compared to consuming the same supplement in the morning and evening. While this study tends to support the idea of taking protein soon after exercise, results of this study should be interpreted with caution because the supplement mix also contains creatine, which by itself increases muscle mass.

Summary

- A person's nutritional state may be categorized as desirable nutrition, in which the body maintains adequate stores for times of increasing need; under-nutrition, which may be present with or without clinical symptoms; and over-nutrition, which can lead to toxicities and various chronic diseases.
- Nutrition recommendations made to the public for health promotion and disease prevention are based on available scientific knowledge. Dietary standards such as the Dietary Reference Intakes provide recommendations for intakes of nutrients and other food components that may be used to plan and assess the diets of individuals and populations.
- The Dietary Reference Intakes (DRIs) represent a set of four types of nutrient intake reference standards used to assess and plan dietary intake. They include: (1) Estimated Average Requirements (EARs), (2) Recommended Dietary Allowances (RDAs), (3) Adequate Intake Levels (AIs), and (4) Tolerable Upper Intake Levels (UIs).
- The DRIs also include calculations for Estimated Energy Requirement (EERs), which may be used to assess whether one's energy intake is sufficient, and Acceptable Macronutrient Distribution (AMDRs), which provide a recommended distribution of macronutrients in terms of energy consumption.
- To follow the Dietary Guidelines, one must keep in mind the five diet-planning principles: (1) adequacy, (2) balance, (3) nutrient density, (4) moderation, and (5) variety. Adequacy means that diet provides sufficient energy and enough of all the nutrients to meet the needs of healthy people; balance involves consuming enough, but not too much, of each type of food; nutrient density concerns the amounts of nutrients that are in a food relative to its energy content; moderation concerns not consuming too much of a particular food; and variety emphasizes the importance of consuming different foods within each food group.
- MyPyramid is designed to translate nutrient recommendations into a food plan that exhibits variety, balance, and moderation. This meal-planning tool incorporates one's physical activity pattern and emphasizes the balance between energy intake

and energy expenditure. It entails six food groups, including grains, vegetables, fruits, oils, dairy products, and meats and beans that are represented in different colors, each with different widths.

- Anyone who exercises regularly should consume a diet that meets calorie needs and is moderate to high in carbohydrate and fluid and adequate in other nutrients such as iron and calcium. In general, the diet of an active individual should contain about 45 to 65 percent of total energy as carbohydrate; 20 to 35 percent of energy as fat; and about 10 to 35 percent of energy as protein.
- Plenty of carbohydrates should be included in the pre-event meal, especially for endurance athletes. High-glycemic index carbohydrates should be consumed by an athlete within two hours following a workout to begin restoration of muscle glycogen stores. Mixing some protein into the post-exercise meal may make glycogen restoration more effective.
- Competitive endurance athletes may utilize glycogen supercompensation regimens to maximize glycogen stores before an event.
- Supplementing carbohydrate and protein post exercise is an important consideration, especially when the time to recover between successive athletic competitions or training sessions is very short. To maximize its efficacy, it is recommended that athletes consume more easily absorbable forms, such as high glycemic index carbohydrate and whey, soon after training or competitions.
- Athletes should consume enough fluid and ultimately restore pre-exercise weight. Sports drinks help replace fluid, electrolytes, and carbohydrate lost during workouts. Their use is especially appropriate and important when continuous activity lasts beyond 60 minutes.

Case study: planning a training diet properly

Tom is training for a triathlon event coming up in three weeks' time. He has read a lot about sports nutrition and especially about the importance of eating a high-carbohydrate diet while in training. He has also been struggling to keep his weight within a range that he feels he can perform to the best of his potential. Consequently, he is trying to eat as little as possible. Over the past two weeks Tom has been feeling weak, and his workouts in the afternoons have not met his expectations. His run times are slower and he shows signs of fatigue after just 20 minutes into his training program.

Tom's dietary records reveal that his breakfast the previous day was a large bagel, a small amount of cream cheese, and a cup of apple juice. For lunch, he had a small salad with low-fat dressing, a large plate of pasta with marinara sauce and broccoli, and a diet soda. For dinner, he had a small broiled chicken breast, a cup of rice, some carrots, and a glass of ice tea. Later, he snacked on fat-free pretzels with a glass of water.

Questions

- Tom is on the high-carbohydrate diet, but why did he experience weakness and fatigue?
- Provide some changes that should be made in Tom's diet, including certain specific foods.
- Are there any other recommendations you may have to help Tom maintain his training quality and prevent fatigue?

Review questions

1 Describe the concepts of "estimated average requirements (EAR)," "recommended daily allowances (RDA)," and "acceptable macronutrient distribution ranges (AMDR)."
2 How would you explain the concept of nutrient density?
3 Estimate your energy requirements using the EER formula. Discuss those major factors that can influence this estimate.
4 Specify the acceptable macronutrient distribution ranges for carbohydrate, fats, and protein.
5 What are the recommended daily intakes of fiber and sugar? Why should we maximize fiber intake and minimize sugar intake as part of healthy eating?
6 How should the total daily fat intake be distributed between saturated, monounsaturated, and polyunsaturated fatty acids? Provide some food examples for each type of fat.
7 What is the recommended intakes of protein for (1) average individuals, (2) endurance-trained athletes, and (3) strength-trained athletes?
8 What are the major nutrients and nutrition parameters found in the Nutrition Facts panel? How are percentage daily values determined?
9 An active person is recommended to make up 55 percent of his total caloric intake as carbohydrate. If his or her average caloric intake is 3000 kcal/day, how much carbohydrate in grams should he or she consume per day?
10 Identify special roles played by carbohydrate and protein in improving athletic performance.
11 What are the recommended intakes of protein for someone pursuing (1) endurance training, (2) resistance training associated with weight maintenance, and (3) resistance training associated with hypertrophy?
12 What is glycogen supercompensation or carbohydrate loading? Explain how this dietary manipulation is carried out.
13 Discuss pre-game nutrition guidelines.
14 What are the key elements of in-game nutrition guidelines? What is the maximal dose of carbohydrate that should be consumed during an endurance event? How is this dose determined?
15 What are the dietary recommendations for replenishing muscle glycogen following an exhaustive exercise?
16 Describe the essence of a ketogenic diet and its positive effects on the brain, fat tissue, and muscle.

Suggested reading

1 Brooks GA, Butte NF, Rand WM, Flatt JP, Caballero B (2004) Chronicle of the Institute of Medicine physical activity recommendation: how a physical activity recommendation came to be among dietary recommendations. *American Journal of Clinical Nutrition*, 79: 921S–930S.
This article reviews the scientific literature regarding macronutrients and energy, and develops estimates of daily intake that are compatible with good nutrition throughout the life span and that may decrease the risk of chronic disease. The article emphasizes the concept of energy balance and suggests that physical activity recommendations must consider one's energy intake status.
2 Burke LM, Cox GR, Culmmings NK, Desbrow B (2001) Guidelines for daily carbohydrate intake: do athletes achieve them? *Sports Medicine*, 31: 267–299.
This article discusses in particular the dietary guidelines designed for athletes to achieve high carbohydrate intakes. It provides recommendations for routine carbohydrate intake, but also analyzes the current status of athletes in meeting their energy needs and dietary goals.

3 Jeukendrup AE (2004) Carbohydrate intake during exercise and performance. *Nutrition*, 20: 669–677.
This article discusses various strategies of consuming or supplementing carbohydrate aimed to enhance athletic performance. Among the major intriguing issues discussed include the type and dose of carbohydrate, the rate of ingestion, and the timing of supplementation.
4 Seal CJ (2006) Whole grains and CVD risk. *Proceedings of the Nutrition Society*, 65: 24–34.
This article provides a thorough review of literature on the protective effect of wholegrains against cardiovascular diseases. Particularly unique is that this article also discusses the underlying mechanisms of such protective effect.

Glossary

Acceptable macronutrient distributions (AMDRs) a standard that provides recommended distributions of macronutrients in terms of energy consumption.

Adequacy means that diet provides sufficient energy and enough of all the nutrients to meet the needs of healthy people.

Adequate intake levels (AIs) standard values that represent the average daily amount of a nutrient that appears sufficient to maintain a specific criterion and often used when DRI and RDA are not available.

Balance consuming enough, but not too much, of each type of food.

Daily value information found on food labels that provides a guide to the nutrients in one serving of food and based on a 2000-kilocalorie diet.

Dietary Guidelines for Americans dietary recommendations issued by the U.S. Department of Health and Human Services (DHHS) to provide specific advice on how good dietary habits can promote health and reduce risk for major chronic disease.

Dietary Reference Intakes (DRIs) a set of nutritional standards used for assessing the adequacy of a person's diet.

Discretionary calories calories allowed from food choices rich in added sugars and solid fat.

Essential nutrients nutrients necessary to sustain life.

Estimated average requirements (EARs) standard values that represent the average daily amount necessary to maintain a specific biochemical or physiological function in half the healthy people of a given age and gender group.

Estimated energy requirements (EERs) a measure used to assess whether one's energy intake is sufficient.

Female athlete triad a condition that includes disordered eating, amenorrhea, and osteoporosis and that is often found in competitive female athletes.

Glycogen supercompensation a diet and exercise regimen aimed to increase muscle glycogen stores to a level greater than that achieved in a typical diet.

Health claims information found on food labels that describes a relationship between a nutrient or a food and the risk of a disease or health-related condition.

Moderation not to consume too much of a particular food.

Nonessential nutrients nutrients the body can make in sufficient amounts when they are needed.

Nutrient content claims information found on food labels that describes the content level of a nutrient in a food.

Nutrient density the amounts of nutrients that are in a food relative to its energy content.

Recommended dietary allowances (RDAs) standard values that represent the average daily amount of a nutrient considered adequate to meet the known nutrient needs of nearly all healthy people of a given age and gender group.

Tolerable upper intake levels (ULs) standard values that represent the maximum daily amount of a nutrient that appears safe for most healthy people.

Variety consuming different foods within each food group.

11 Ergogenic aids and supplements

Contents

Key terms

- β-hydroxy-β-methylbutyrate
- ATP citrate lyase
- Boron
- Caffeine
- Chromium
- Creatine
- Doping
- Ergogenic
- Glutamine
- Hydroxy citric acid
- L-carnitine
- Phosphate loading
- Synephrine
- Androstenedione
- Bicarbonate
- Branched-chain amino acids
- Casein
- Coenzyme Q_{10}
- Dehydroepiandrosterone
- Ephedrine
- Ergolytic
- Glycerol
- Inosine
- Nitric oxide
- Sports supplements
- Whey

Ergogenic aid: an area of complexity and controversy

By nature, athletes demand a competitive attitude. The athlete may desire to outperform the opponent, or may compete with themselves while striving to maximize personal potential. This drive to success has fueled a sustained growing market of sports supplements. Many men and women at all levels of prowess use pharmacologic and chemical agents, believing that a specific substance positively influences strength, power, or endurance. Such a quest for reaching the maximum of physical performance or aesthetics can be traced back to ancient times. For example, athletes of ancient Greece reportedly used hallucinogenic mushrooms and ground dog testicles for ergogenic purposes, while athletes of the Victorian era routinely used caffeine, alcohol, nitroglycerine, heroin, cocaine, and rat poison strychnine to gain a competitive edge. Today's athletes are perhaps more likely than their predecessors to experiment with purported ergogenic aids even though most of them may not have been substantiated. Two key factors important to athletic success are genetic endowment and state of training. At high levels of competition, athletes generally have similar athleticism and have been exposed to similar training methods. Therefore, they are fairly evenly matched. Given the emphasis on winning, many athletes are always searching for a "magic" ingredient that provides them with that extra winning edge. When such ingredients are harmless they are merely a waste of money, but when they impair performance or harm health they can waste athletic potential and cost lives. This chapter will review some of the commonly used nutritional substances and ergogenic products that have been claimed to affect basal metabolism, food consumption, energy transformation, fat utilization, and/or sports performance.

What is an ergogenic aid?

The word "**ergogenic**" is derived from the Greek words *ergo* (meaning work) and *gen* (meaning production of), and is defined as increasing work or potential to do work. Ergogenic aids consist of substances or procedures that improve physical work capacity, physiological function, or athletic performance. An ergogenic aid does not need to be nutritional or pharmacological; it can also be mechanical, psychological, or physiological. Mechanical aids are designed to increase energy efficiency, thereby improving mechanical advantage. One example of using such an ergogenic aid is where runners wear lightweight racing shoes so that less energy is needed to move the legs. Psychological aids are designed to enhance the psychological process or mental strength during sports competitions. One example of using such an ergogenic aid is the mental conditioning through hypnosis that some athletes use to minimize distractions, thereby enhancing their performance. Physiological aids, which will be further discussed along with nutritional or pharmacological aids in this chapter, are designed to augment natural physiological processes to increase physical power. Blood transfusion and bicarbonate loading are the two common examples of using such aids for enhancing performance. This chapter will be mostly devoted to the discussion of various nutritional and pharmacological ergogenic aids. These ergogenic aids, collectively regarded as **sports supplements**, are concerned with the use of nutrients or chemical compounds, or drugs believed to be effective in enhancing physiological or psychological functions. For example, anabolic steroids, drugs that mimic the actions of the male sex hormone testosterone, may increase muscle size and strength, but, to avoid potential side-effects of taking this drug, strength-trained athletes may consider using a nutritional approach by taking protein supplements instead for the same purpose.

Why are ergogenic aids popular?

Weight loss and muscle gain are important concerns for many athletes as well as for individuals not involved in athletic training. Because achieving these goals is very difficult with conventional methods such as increasing energy expenditure through physical activity, using supplements that may potentiate or replace the effect of training becomes an attractive option. Many athletes believe that certain foods may possess magic qualities. Since sports supplements are not regulated by the government agency, such as the FDA, the media become consumers' leading source of nutrition information, but many news reports of nutrition research often provide inadequate depth for consumers to make wise decisions. For example, isolated nutrition facts may be distorted or results of a single study or studies from non-peer-reviewed journals are used to market a specific product. Many of these products are endorsed by professional athletes, giving products an aura of respectability. Specific supplements may also be recommended by coaches and fellow athletes. However, research studies reveal that many coaches have poor backgrounds in nutrition, suggesting that misconceptions adopted by coaches may be perpetuated in their athletes. It has been estimated that more than 50 percent of all athletes have used some form of nutritional or pharmacological supplement and some athletes use several supplements at the same time and in very high doses (Burke and Reed 1993). Use of dietary supplements has also been found to be prevalent among high school and collegiate athletes, military personnel, and fitness club members.

Non-regulation of sports supplements

In contrast to prescription drugs, which are carefully regulated, nutrition supplements and ergogenic aids receive very little government oversight, and manufacturers and

retailers have enormous freedom in making claims to promote the product. For example, the FDA strictly regulates the clinical testing, advertising, and the promotion of foods and drugs, so that those products which fail clinical trials or are marketed by unproven claims will not be allowed to go on sale. Drugs are extensively tested for safety before they may be sold, but nutritional supplements are not. The FDA regulates nutritional supplements under a different set of regulations than those covering "conventional" foods and drug products. In accordance with the Dietary Supplement Health and Education Act of 1994, the FDA requires that the dietary supplement manufacturer is responsible for ensuring that a dietary supplement is safe before it is marketed, and will take action against any unsafe dietary supplement product after it reaches the market. Generally, manufacturers do not need to register their products with the FDA nor get FDA approval before producing or selling dietary supplements. The dietary supplements being referred to by the FDA are vitamins, minerals, herbs and botanicals, amino acids, dietary substances intended to supplement the diet by increasing the total dietary intake (e.g., enzyme or tissue), or any concentrate, metabolite, constituent, or extract.

Legality of ergogenic aids

The use of pharmacological agents to enhance performance in sport has been prohibited by the governing bodies of most organized sports. The use of drugs in sports is known as **doping**, and the Medical Commission of the International Olympic Committee (IOC) has provided an extensive list of drugs and doping techniques that have been prohibited (Table 11.1 and www.usada.org). The specific banned substances and methods listed by the World Anti-Doping Agency are provided in Appendix F. At the present time, all essential nutrients are not classified as drugs and are considered legal for use in conjunction with athletic competition. Most other food substances and constituents sold as dietary supplements are also legal. However, some dietary supplements are prohibited, such as dehydroepiandrosterone (DHEA) and androstenedione because they are classified as anabolic steroids. Others may have prohibited substances included. For example, many weight loss products contain ephedrine or amphetamine, a stimulant that is considered an illegal drug by many sports organizations. It is hoped that, with pending legislation, all ingredients will be listed in correct amounts on dietary supplement labels. In the meantime, athletes should consult with appropriate authorities before using any sports nutrition supplements marketed as performance enhancers, although the use of sports supplements is completely at the athlete's own risk, even if the supplements are "approved" or "verified."

Table 11.1 International Olympic Committee Medical Commission doping categories

Doping classes	• Stimulants • Narcotics • Anabolic agents • Diuretics • Peptide and glycoprotein hormones and analogs
Doping method	• Blood doping • Pharmacological, chemical, and physical manipulation
Classes of drugs subject to certain restrictions	• Alcohol • Marijuana • Local anesthetics • Corticosteriods • β-blockers • Specified β2-agonists

Critical evaluation of ergogenic aids

Manufacturers expend considerable money and effort to show a beneficial effect of an ergogenic aid. Often, however, a "placebo effect" and not the aid per se improves the performance due to psychological factors. In other words, the individual performs at a high level because of the suggestive power of believing that a substance or procedure should work. Athletes and others must critically examine claims made by the dietary supplements industry, including the scientific evidence that supports the claims. The following are six areas for questioning the validity of research claims concerning the efficacy of ergogenic aids.

Rationale and justification

Does the study have s sound rationale and clear hypothesis that a specific treatment or supplement should produce an effect? A well-designed study has a clear hypothesis and a strong theoretical basis for the expected outcome. For example, a theoretical basis exists to believe that ingesting carbohydrate solution will provide an extra energy source to improve endurance performance. However, no rationale exists to hypothesize that carbohydrate loading should enhance short-term power performance such as a 100- and 200-m dash. In addition, some studies are designed with a "shotgun" approach that lacks a clear hypothesis. These types of studies often wind up measuring many different variables, some of which bear no theoretical link to the supplement being examined. The more variables examined, the greater chance that some of them will change.

Subjects

Was the study conducted using cells, muscles, animals, or humans? Often results are extrapolated from findings in the cell cultures. These *in-vitro* experiments can help our understanding of molecular interactions at cellular level. However, *in-vivo* situations may be very different. Muscle cells in the body may behave differently than isolated muscle cell preparations. Even if living animals are used, the physiology and metabolism of animals can be very different from those of humans. Compared with humans, rats have a relatively small store of intramuscular triglycerides. In addition, high-fat diets in rats have been shown to improve exercise performance, but no evidence indicates that high-fat diets improve performance in humans. Even within humans, caution is needed to generalize findings across populations of different age, gender, training level, and nutrition and health status. Alcohol seems to impact women more profoundly than men due to body-size difference. Coenzyme Q_{10} supplementation improves VO_2max and exercise capacity in cardiac patients, but has no such benefits in healthy individuals. In addition, supplemental iron enhances aerobic capacity in a group with iron-deficient anemia. However, one cannot generalize that iron supplementation will benefit all individuals.

Research design

Were the experimental trials randomized? Was the study's double-blind placebo controlled? How were extraneous variables controlled? These are the important questions in terms of research design that must be considered by investigators prior to the start of data collection. If subjects "self-select" into a treatment group, a question will arise as to whether the results are produced by the treatment per se or by a change due to subjects' motivation. For example, the desire to enter a weight loss program may elicit behaviors that produce weight loss independent of the treatment. Randomization reduces the

confounding effects of variables that were not controlled or could not be controlled. However, great difficulties exist in assigning truly random samples of subjects into a treatment and a control group. When a small number of subjects (i.e., n=10) are used, a so-called counterbalanced design is preferred. A counterbalance procedure is to assign subjects into either a treatment or a control condition, but the decision as to which five of the ten subjects will take part in which condition is random. In this procedure, each group receives treatments in a different order. In other words, half of the subjects will take the supplement first; the other half will take the placebo first. Failure to randomize treatments in a study may confound the outcome and hence make any conclusion untrustworthy.

The ideal experiment to evaluate the ergogenic effect of a supplement requires that treatment and control subjects remain unaware or "blinded" to the substance administered. To achieve this goal, while all subjects should receive a similar quantity and/or form of the proposed aid, the control group receives an inert compound or placebo. The placebo treatment evaluates the possibility of subjects performing well simply because they receive a substance they believe should benefit them. If subjects have prior knowledge or expectations with respect to a treatment or supplement, their performance could be affected. To further reduce bias from influencing the experimental outcomes, those who administer the treatment and measure the outcomes must also be unaware of which subject receives the treatment or placebo. In such a double-blinded experiment, both investigator and subjects remain unaware of the treatment condition. It must be noted that with some nutrition interventions, matching placebos, especially those that produce the same taste, are difficult to find. Therefore, despite the use of a double-blind, placebo control procedure, some studies may still bear the limitation associated with the fact that subjects may be aware of what they receive.

In an ideal study, all variables and conditions should be made as identical as possible, so that the only difference between the experimental trials is the treatment, whether supplement or placebo, each group receives. In doing so, all observed changes may be ascribed with great confidence to the treatment.

Testing and measurement

Reproducible, objective, and valid measurement tools must be used to evaluate research outcomes. For example, it would not be ideal to use a step test to determine one's aerobic capacity or to use infrared interactance to estimate one's body composition because these tools have a relatively large margin of error, especially if the change to be detected is rather small. If a treatment or supplement is said to have no effect, perhaps the particular method used in the study was not sensitive enough to pick up the small differences. A small change in performance (i.e., <3 percent) that is undetectable in a laboratory setting may determine success or failure in a sports event.

Conclusions

The conclusions of a research study must logically follow the research outcomes that are supported by statistical analysis. Sometimes, investigators who study ergogenic aids extrapolate conclusions beyond what their data suggest. The implication and generalization of research findings must remain within the subjects studied, the context of measurements made, and the magnitude of the response. For example, increases in testosterone levels as a result of a dietary supplement reflect just that; they do not necessarily indicate an increase in muscle size and contractile function. A correct

interpretation of statistical analysis may be another obstacle to many consumers. Investigators must ensure that the appropriate inferential statistical analysis is used to quantify the potential that chance caused the research outcome. The finding of statistical significance of a particular treatment only means that a high probability exists that the result did not occur by chance. One must also evaluate the magnitude of an effect for its impact upon actual performance. For example, a reduction in time of running 100 m by 0.5 of a second may not reach statistical significance, yet it could mean a difference between the first and last place.

Dissemination

One way to ensure that a research study is of high quality is to use a peer review system. Most scientific journals require that reports of studies be reviewed by two or three experts in the field who did not take part in the research being evaluated. Before an article can be published, these scientists must agree that the experiments were well designed and conducted and that the results were analyzed and interpreted correctly. Peer review provides a measure of quality control over scholarship and interpretation of research findings. Publications in popular magazines or online journals do not undergo the same rigor of evaluation as peer review. High-quality nutrition articles may be found in peer-reviewed journals, such as the *American Journal of Clinical Nutrition*, *The Journal of Nutrition*, the *Journal of American Dietetic Association*, the *New England Journal of Medicine*, and the *International Journal of Sports Nutrition and Metabolism*.

Sports foods

Products manufactured by companies such as MET-Rx, EAS, Power Bar, and Gatorade are some of the biggest sellers of sports foods in this market. Sports foods come in the form of bars, shakers, drinks, and gels, and they tend to be more complex and food-like, and often contain one or more kinds of nutrients. The most salient feature of these products is that they contain energy sources, such as carbohydrate. Some of these products are consumed before, during, or after exercise, and others are meant to serve as partial or full meal replacements.

Sports bars

Sports bars represent one of the fastest-growing areas of the sports food industry. These products provide energy as well as other essential nutrients. Their composition may vary tremendously based on the intended consumer and purpose of the sports food. For example, some sports bars are marketed as a quick and high energy source, so that they may be used before or after intense training or sports competitions. Others are designed to be meal replacements that contain a high amount of protein and/or fiber. The energy and nutrient formulation for some of the more popular sports bars is presented in Table 11.2.

Carbohydrate is usually the energy foundation of many sports bars that are to be consumed before and after exercise. In these products, corn syrup or high-fructose corn syrup (HFCS) is the common carbohydrate ingredient, and both are based on partially digested cornstarch. Other carbohydrate ingredients include fruit juice concentrates and dried fruit, oat bran, brown rice, and rice crisps. Many sports bars also contain fiber. Having fiber allows a slower and more even absorption of carbohydrate, thereby producing a lower insulin response. However, sports bars rich in fiber should not be used just before or during exercise because they can cause intestinal discomfort.

Table 11.2 Nutrient composition of selected top-selling sports bars

Sports bar	*Energy (kcal)*	*Carbohydrate (g)*	*Fiber (g)*	*Protein (g)*	*Fat (g)*
Balance	200	22	<1	14	6
Promax	270	39	1	20	4.5
Ironman	230	20	0	16	7
PowerBar Protein Plus	300	38	1	23	6
Myoplex Deluxe	340	37	1	30	9
Power Bar Performance	230	45	3	10	2
Clif Bar	250	45	5	10	5
Zone perfect	210	21	1	15	7
Snickers/Marathon	220	32	2	10	7

The protein component of sports bars is largely based on proteins isolated from milk and/or egg whites because of their higher biological values (see Chapter 2). Amino acids, such as branched-chain amino acids, are often added to create a more desirable composition. Manufacturers of sports bars often trademark their protein/amino acid source as a proprietary blend. Fat contributes energy, flavor, and sensory aspects of sports bars. However, it is not the focus among the energy–nutrient ingredients.

The energy–nutrient ratio varies among sports bars depending on their purpose. Some sports bars have a carbohydrate–protein ratio of approximately 4:1 or 3:1, which is ideal for use during recovery. Some sports bars derive more than 60 percent of energy from carbohydrate, which makes them a perfect choice for a pre-game meal. In some other sports bars, protein accounts for more than 50 percent of the energy, a value higher than carbohydrate. These bars are not designed to be an energy source, but rather are used for enhancing protein synthesis and possibly muscle size.

Vitamins and minerals are typically added to sports bars, especially those directly involved in energy metabolism, such as B vitamins, magnesium, zinc, and iron. Adding nutrients such as vitamins C and E as well as copper, iron, lipoic acid, and glutathione often reflects an attempt to optimize antioxidant status. In addition, some sports bars contain other ergogenic substances such as creatine, carnitine, and HMB.

Sports drinks

Sports drinks are popular among a broad range of athletes. Research has demonstrated that carbohydrate-containing sports drinks can enhance performance during endurance and intermittent high-intensity exercise, and may also benefit competitive weight-lifters. Sports drinks may be split into two categories: (1) fluid and electrolyte replacement drinks in which the carbohydrate content is relatively low; and (2) drinks that contain a higher carbohydrate formulation. The former are more appropriate for use during exercise, whereas the latter are better suited for consumption after training or in preparation for an upcoming event. This second category is also referred to as recovery or loading beverages. The composition of the two sports drink categories is listed in Table 11.3.

In sports drinks, carbohydrate is typically provided as glucose, sucrose, fructose, corn syrup, maltodextrins, and glucose polymers. These carbohydrates usually make up about 4 to 8 percent of a fluid/electrolyte replacement drink and >10 percent of a recovery/loading beverage. One of the most important considerations with regard to carbohydrate percentage is how it influences the rate of gastric emptying. As carbohydrates exceed 8 percent of the solution, gastric emptying begins to slow down. Therefore, the fluid/electrolyte replacement drinks are often used during endurance events such as

Table 11.3 Comparison of energy and carbohydrate content of Gatorade and energy drink

Nutrition facts (240 ml or 8 oz)	*Fluid and electrolyte replacement drink*	*High-carbohydrate energy drink*
Total energy	50 kcal	210 kcal
Total carbohydrate	14 g	52 g
Sugar	14 g	28 g
Other carbohydrate	0 g	24 g
Protein	0 g	0 g
Fat	0 g	0 g
Sodium	110 mg	135 mg
Potassium	30 mg	70 mg

distance running and cycling as well as intermittent sports such as soccer, field hockey, lacrosse, tennis, and hockey. This is because during exercise gastrointestinal motility and absorption decreases. As shown in Table 11.3, the amount of carbohydrates in the fluid/electrolyte replacement drinks is only a quarter of that in the recovery/loading-type drinks.

The purpose of fluid/electrolyte replacement drinks is not only to replace carbohydrate and water, but also to provide sodium and chloride, which are the main electrolytes found in sweat and are frequently subjected to heavy loss during prolonged exercise. This type of sports drink also contains potassium, though in a smaller amount. Potassium, alone with sodium and chloride, plays an important role in neuromuscular function. Other ingredients that may be found in both types of sports drink include phosphorus, chromium, calcium, magnesium, iron, caffeine, and certain vitamins.

Whether or not carbohydrate consumption in amounts typically provided in sports drinks (4 to 8 percent) improves performance in events lasting one hour or less has been controversial. Current research supports the benefit of this practice especially in athletes who exercise in the morning after an overnight fast when liver glycogen is low. Thus, providing exogenous carbohydrates under these conditions would help maintain blood glucose levels and improve performance. Accordingly, performance advantages in short-duration activities may not be apparent when exercise is conducted in the non-fasting state. For longer events, consuming 0.7 g of carbohydrate per kg body weight per hour (approximately 30 to 60 g) has been shown to extend endurance performance (Coggan and Coyle 1991, Currell and Jeukendrup 2008). Ingesting carbohydrates during exercise is even more important in situations where athletes have not carbohydrate-loaded, consumed pre-exercise meals, or restricted energy intake for weight loss. To be more effective, ingestion of carbohydrates should be done at 15- to 20-minute intervals throughout exercise (McConell *et al.* 1996). If the same total amount of carbohydrate and fluid is ingested, the form of carbohydrate does not seem to matter – some athletes may prefer to use a sports drink, whereas others may prefer to eat a solid or gel and consume water.

Several factors may influence the rate of absorption of sports drink ingredients and they include the temperature and concentration or osmolarity of a sports drink. With regard to temperature, cooler solutions (i.e., 5 to 15°C) may empty from the stomach more quickly than warmer or hot solutions. In addition, cooler drinks are more enjoyable and therefore may promote greater consumption. This is why sports drinks are often kept in coolers and poured into cups for athletes to consume during many sporting events. However, one should keep in mind that melting ice in a cooler dilutes the drink. Osmolarity is a measure of solute concentration of a solution and tends to draw

water, and the greater the osmolarity of a solution the greater the ability of this solution to attract water. As the particle concentration within the stomach and small intestine exceeds that in the blood or extracellular fluid, water is drawn in by osmotic force. This may in turn reduce the intestinal absorption of fluid as well as carbohydrates. Sports drinks designed for use during exercise often contain lower concentrations of carbohydrate (i.e., 4 to 8 percent) aimed to facilitate intestinal fluid absorption.

Sports supplements

The term sports supplements is used in this text to be inclusive of both nutritional and pharmacological ergogenic aids. Indeed, of possibly more than 500 supplements on the market, some of them are common nutrients or their derivatives, whereas others may be considered chemical agents purported to enhance sport performance. Despite such a large quantity of ergogenic aids, the fundamental working mechanism of each may be explained by one or more of the following: (1) to act as a central or peripheral nervous system stimulant; (2) to increase storage or availability of a limiting substrate; (3) to act as a supplemental fuel source; (4) to reduce performance-inhibiting metabolic by-products; (5) to facilitate recovery; and (6) to enhance tissue synthesis. The following includes a more in-depth discussion on some of the commonly used ergogenic aids. Readers may wish to consult Table 11.4 for a quick reference in terms of their description, action, and major claims. Note that ergogenic effects of carbohydrate, such as glucose feeding and carbohydrate loading, are covered in Chapter 10.

Arginine, ornithine, and lysine

Lysine is an essential amino acid and arginine is considered conditional or semi-essential because it may become essential during periods of growth. Ornithine is a non-essential amino acid not found in proteins but important for efficient nitrogen removal in the urea cycle. This amino acid is supposed to also enhance the efficiency of intestinal absorption. These amino acids may be purchased as individual supplements or in a combination sometimes marketed as "natural growth hormone." This is because supplementation with these three amino acids has been proposed to augment growth hormone levels in the circulation, leading to greater muscle development (Chromiak and Antonio 2002).

Such a claim is based on early studies involving individuals who had suffered significant burns. For example, it was found that when large doses of ornithine were given to burn patients intravenously, their blood growth hormone levels were increased (Donati *et al.* 1999). It was also found that these patients established a positive nitrogen balance more quickly in days following the treatment (Donati *et al.* 1999, De Bandt *et al.* 1998). An increased release of growth hormone was also demonstrated in healthy but untrained subjects who underwent oral supplementation of combined arginine and lysine (Isidori *et al.* 1981, Suminski *et al.* 1997). However, studies that involved weight-lifters and body builders failed to show an increase in blood growth hormone concentrations when these amino acids were given orally (Fogelholm *et al.* 1993, Lambert *et al.* 1993). These athletes experience the natural increase in growth hormone regularly, due to their training bouts. This may have limited the ability of these athletes to benefit further from amino acid supplementation. An important consideration regarding the efficacy of amino acid supplementation is that even in the studies that observed an increase in growth hormone, the research protocols did not extend to assess changes in lean body mass, strength, and anaerobic performance. Studies involving burn patients provided the three amino acids intravenously and at high dosages. Therefore, these amino acids, once

they have entered the circulation, can exert their effect directly. On the other hand, oral ingestion of these amino acids requires that they must enter the liver first before being further used. It is likely that the liver can metabolize most of these amino acids, leaving the remainder to be of insufficiency in producing their action.

Bicarbonate loading

Dramatic alterations in acid–base balance of the intracellular and extracellular fluids occur when maximal exercise is performed for between 30 seconds and several minutes, such as 400-meter, 800-meter, and 1500-meter running, track cycling events, and speed skating. This is because muscle fibers rely predominantly on anaerobic energy transfer. As a result, significant quantities of lactate accumulate, with a concurrent fall in intracellular pH. An increased accumulation of H^+ in muscle cells can reduce the calcium sensitivity of the contractile proteins, thereby impairing muscle function (Chin and Allen 1998, Street *et al.* 2005).

The body uses several systems to adjust and regulate acid–base balance. Chemical buffers provide a very effective and rapid way of normalizing the H^+ concentration. Other systems include exhalation of CO_2 via pulmonary ventilation and excretion of H^+ via the kidneys. The primary chemical buffers in the muscle are phosphates and tissue proteins. The most important buffers in the blood are proteins, hemoglobin, and bicarbonate. During intense exercise, as intracellular buffers are insufficient to buffer all the hydrogen ions formed, efflux of H^+ into the circulation increases. In this context, maintaining high levels of extracellular **bicarbonate** can facilitate the release of H^+ from the cells and thus delay the onset of intracellular acidosis. The mechanism by which bicarbonate supposedly exerts its action is through the buffering of H^+ in the blood, not in the muscle as is often claimed. The buffering of H^+ in the blood, however, increases the efflux of H^+ from the muscle. The following illustrates the process of how bicarbonate (e.g., HCO_{3-}^{1}) acts against excessive acid production:

$$HCO_{3-}^{1} + H^+ \longleftrightarrow H_2CO_3 \longleftrightarrow H_2O + CO_2$$

Research in this area has produced conflicting results, but they appear to be caused by diverse doses of bicarbonate or different types of exercise used to evaluate the ergogenic effects of bicarbonate loading. It appears that a minimal dose of bicarbonate ingestion is needed to improve performance (Horswill 1995). A dose of 200 mg/kg body weight or higher ingested one to two hours before exercise seems to improve performance in most studies which used exercises that lasted for longer than a minute, whereas doses less than 100 mg/kg body weight do not affect performance. A 300 mg/kg body weight seems to be the optimum dose from performance perspective, but doses higher than 300 mg/kg body weight may be accompanied by gastrointestinal problems, including bloating, abdominal discomfort, and diarrhea.

No ergogenic effect emerges for typical resistance exercises or exercises that last for less than a minute (e.g., squat, bench press, jump). This may be attributed to the fact that these ultra-short-term activities generally have lower absolute anaerobic metabolic load compared with continuous, maximal whole-body activities. Bicarbonate loading with all-out effort of less than a minute improves performance only with repetitive exercise bouts, which in accumulation can produce high intracellular H^+ concentrations (Bishop *et al.* 2004). Bicarbonate loading does not benefit low-intensity, aerobic exercise because pH and lactate remain near resting levels. However, some research indicates the benefits in aerobic exercise of high intensity (McNaughton *et al.* 1999, Potteiger *et al.* 1996). For example, using a 30-km time trial, Potteiger *et al.* (1996) found that the race

Table 11.4 Description of selected sports supplements and their ergogenic claims

Ergogenic aids	*Description*	*Actions/claims*
Arginine, ornithine, and lysine	Lysine: an essential AA; arginine: semi-essential AA; ornithine: non-essential AA not found in proteins but important for nitrogen removal	Increases growth hormone release, thus muscle development
Biocarbonate	A chemical buffer found primarily in extracellular fluid	Maintains acid-base balance by buffering hydrogen ions produced from working muscle, thereby improving anaerobic performance and performance of intense endurance events
Boron	A trace mineral involved in bone mineral metabolism, steroid hormone metabolism, and membrane functions	Increases testosterone production that helps with tissue building and anabolic actions
BCAA	Leucine, isoleucine, and valine and essential amino acids	Serve as additional energy fuel; enhance protein synthesis; prevent or attenuate the excessive loss of protein; reduce mental fatigue
Caffeine	Naturally occurring substance found in coffee, tea, and chocolate	Improves cognitive function, increases fat use, and spares muscle glycogen, which benefit both anaerobic and aerobic performance
Chromium	A trace mineral found in foods such as brewer's yeast, cheese, broccoli, wheatgerm, nuts, liver, and egg yolk	Potentiates insulin action and thus helps with anabolic tissue building
Carnitine	A substance found in relatively high quantities in meat	Functions as carrier protein that transports long-chain fatty acids into mitochondria, thereby improving endurance performance
Co-enzyme Q_{10}	Also referred to as ubiquinone and a integral component of the mitochondrion's electron transport system	Plays an important role in oxidative phosphorylation, thereby improving aerobic capacity and endurance performance
Creatine	A nitrogen-containing molecule produced from the liver, kidneys, and pancreas	Augments PCr levels and buffers hydrogen ions, thereby improving performance of ultra-short/short terms events
DHEA and Androstenedione	Precursors to testosterone and produced mainly in the adrenal glands	Improves lean body mass, thereby improving strength. DHEA may also enhance immune function and protects against cardiovascular diseases

Ephedrine	Also referred to as Ma-Huang and naturally occurring in some botanicals	Functions as a stimulant like catecholamine to improve body composition and both aerobic and anaerobic performance
Glutamine	A naturally occurring nonessential amino acid and most abundant amino acid in human muscle and plasma	Enhances protein synthesis and protects against infections or illness associated with exhaustive exercise
Glycerol	A component of the triglyceride molecule and an important constituent of the cells' phospholipid plasma membrane	Induces hyperhydration, decreases heat stress and improves performance
Hydroxycitric acid (HCA)	A derivative of citric acid found in a variety of tropical plants, including garcinia cambogia	Functions as a weight loss supplement by inhibiting fatty acid biosynthesis and/or suppressing appetite
HMB	A metabolite of the essential amino acid leucine and also found in red meats, catfish, asparagus, cauliflower, and grapefruit	Reduces muscle damage and suppresses protein degradation associated with intense physical effort
Inosine	A nucleoside comparable to adenine, which is one of the structural components of ATP	Increases ATP stores, favoring strength and power athletes and involved in the production of 2,3-DPG that facilitates the delivery of oxygen into tissues
Nitric oxide (NO)	A messenger molecule derived from L-arginine, nitrate (NO_3^-) or nitrite (NO_2^-)	Causes vasodilation, thereby increasing tissue blood flow and oxygen delivery
Phosphate	A major mineral found mainly in bones, and also a component of ATP and 2,3-DPG	Increases ATP synthesis and oxygen extraction in muscle cells, thereby improving performance of both anaerobic and aerobic events
Synephrine	Also known as p-synephrine, an extract from the bitter or sour orange	Functions as a stimulant that increases thermogenesis
Whey and casein	Milk proteins derived from the cheese-making process with whey being digested more quickly and casein sustaining longer for its effect	Enhances muscle recovery and adaptations by providing more amino acids needed for protein synthesis

times of trained male cyclists were better after consuming a buffering solution (500 mg/kg body weight) before exercise than in placebo trials, and this increase in performance was accompanied by an elevated level of blood pH throughout the exercise.

Boron

Boron is an essential trace mineral involved in bone mineral metabolism, steroid hormone metabolism, and membrane functions. It is found in non-citrus fruits, leafy vegetables, nuts, and legumes. Boron has been studied in relation to osteoporosis. One of these studies found that 48 days of boron supplementation increased estrogen and testosterone levels of post-menopausal women (Nielsen *et al.* 1987). It also decreased the excretion of calcium, phosphorous, and magnesium in urine. Therefore, it appears that boron supplementation helps improve bone mineral density. The finding that boron supplementation increased testosterone levels has been singled out disproportionately and extrapolated to the claim that it may improve muscle growth and strength. However, what is often overlooked is that the participants of the study were postmenopausal women who were on a boron-deficient diet for four months. In addition, one must be aware that boron supplementation raised serum estrogen levels as well. In studies involving athletic populations, boron supplementation has not been proven to increase testosterone levels. For example, male body builders who took 2.5 mg of boron daily for seven weeks saw no changes in measures of testosterone, lean body mass, and strength as compared to the placebo condition (Ferrando and Green 1993). On the basis of these studies, boron supplementation does not appear to confer any ergogenic benefit.

Branched-chain amino acids (BCAA)

Branched-chain amino acids (BCAA), leucine, isoleucine, and valine, are not synthesized by the body and therefore must be introduced with the diet. In the late 1970s, BCAA were suggested to be the third fuel for skeletal muscle after carbohydrate and fat (Goldberg and Chang 1978). The entire metabolic pathway for BCAA involves sequential steps of transamination of BCAA to produce branched-chain alpha-keto acids followed by decarboxylation of alpha-keto acids to form acetyl-CoA to be used in the Krebs cycle or gluconeogenesis. Exercise has been shown to promote oxidation of BCAA by activating catabolic enzymes. For this reason, BCAA were considered ergogenic in that they can provide athletes with extra fuel. However, studies designed to show positive effects of BCAA on athletic performance have failed to confirm this hypothesis. It has been found that the activities of the enzymes involved in oxidation of BCAA were too low to allow a major contribution of BCAA to energy expenditure (Wagenmakers *et al.* 1991).

Claims have also been made that BCAA supplementation can prevent or attenuate protein breakdown in muscle. After intense exercise, protein breakdown remains elevated for several hours and protein synthesis increases for as long as two days. Muscle recovery needs a positive muscle protein balance that occurs when muscle protein synthesis exceeds muscle protein breakdown. In order to reduce exercise-induced muscle protein breakdown and improve muscle recovery, BCAA supplementation was examined in humans. It was reported that an oral supplement of BCAA at 77 mg/kg body mass administered 20 minutes before exercise increased intracellular and arterial BCAA levels coupled with significantly lower release of BCAA during 60-minute exercise at ~70 VO_2max as compared to a control trial (MacLean *et al.* 1994). Similar effects were also observed in a study in which subjects consumed BCAA at 100 mg/kg body mass before, during, and after a prolonged exercise of similar intensity (Blomstrand and Saltin 2001).

BCAA supplementation may spare muscle protein during prolonged and intense exercise. However, caution should be exercised, as studies from other laboratories have failed to confirm such positive effects of BCAA on protein balance (Nair *et al.* 1992, Frexes-Steed *et al.* 1992).

Eric Newsholme, a biochemist at Oxford University, postulated that high levels of serum-free tryptophan (fTRP) in conjunction with low levels of BCAA, or a high fTPR:BCAA ratio, may be a major factor that causes fatigue during prolonged endurance exercise. This contention was developed based on the fact that fTRP is used in the production of serotonin, which is believed to play a key role in the onset of fatigue. BCAA on the other hand can compete against fTRP for the carrier-mediated entry in the central nervous system, thus mitigating the production of serotonin. When BCAA levels decrease, a higher percentage of tryptophan can enter the brain cells. Tryptophan is then converted into serotonin to produce a relaxation effect that ultimately causes a fatigued sensation and resulting decrease in exercise performance (Davis *et al.* 2000). It has been suggested that the ingestion of BCAA may raise the plasma BCAA concentration and thus reduce transport of fTRP into the brain and thus improve performance. If this central fatigue hypothesis is true, then the opposite must also be correct; that is, consumption of tryptophan before exercise should reduce the time to exhaustion, thereby hampering performance. Nevertheless, a study by Stensrud *et al.* (1992) demonstrated no differences in exhaustive running performance between those who were on tryptophan and those who were on a placebo. It appears that further research is still needed in order to substantiate this claim associated with BCAA.

More recently, investigators have focused on the effects of BCAA on the exercise-induced muscle damage and its recovery. As discussed in Chapter 7, intense exercise that involves eccentric muscle contraction will lead to delayed onset muscle soreness (DOMS), a syndrome that occurs 24 to 48 hours after intensive physical activity. In individuals with DOMS, full muscle strength may not return for days or even weeks. Therefore, a variety of countermeasures such as stretching, ice, compression, massage, anti-inflammatory drugs, and a host of dietary supplements have been tried, with limited success. One promising strategy is the use of BCAA. Recent research has revealed that compared to the placebo group, athletes who consumed 20 grams of BCAA daily in two 10-gram doses in the morning and evening experienced a significantly lower increase in blood levels of creatine kinase, a marker of muscle damage upon competing 100 consecutive drop-jumps (Howatson *et al.* 2012). The BCAA group also demonstrated lower levels of muscle soreness and faster recovery of muscle force post exercise. These findings suggest that BCAA supplementation can mitigate exercise-induced muscle damage and allow for a more rapid return of muscle performance.

Caffeine

Caffeine occurs naturally in a variety of beverages and foods, including coffee, tea, and chocolate (Table 11.5). It is consumed by most adults throughout the world. It is estimated that the daily intake of caffeine for an average adult is approximately 3 mg kg^{-1}, 80 percent of which is consumed in the form of coffee (Barone and Roberts 1996). Caffeine is recognized as a food and a drug in both the scientific and regulatory domains. It is, however, not a typical nutrient and is not essential for health. There are several over-the-counter medications containing from 30 to 100 mg of caffeine. These include cold medicines, diuretics, weight loss products, and preparations that help people stay awake. Caffeine can be rapidly absorbed in the digestive tract and distributed to all tissues. It can also easily cross the blood–brain barrier to reach the tissues of the central nervous system.

Table 11.5 Caffeine content of some common foods, beverages, and medicines

Common product	*Serving size*	*Caffeine (mg)*
Baking chocolate	28 g (1 oz)	45
Chocolate candy	57 g (2 oz)	45
Chocolate milk	237 ml (8 oz)	48
Mello yellow	355 ml (12 oz)	51
Mountain dew	355 ml (12 oz)	54
Cola beverages	355 ml (12 oz)	32–65
Instant coffee	177 ml (6 oz)	54–75
Brewing coffee	177 ml (6 oz)	150–200
Ice tea	355 ml (12 oz)	150
Hot tea	177 ml (6 oz)	65–105
Aspirin products	Standard dose	30–125
Vivarin tablets	1 tablet	200

Unlike ephedrine, the existing literature appears to be more definitive in support of ergogenic effects of caffeine on cognitive and physical performance. On the other hand, caffeine alone is not as effective in prompting weight loss. Caffeine's cognitive and behavioral effects have been documented in a number of well-controlled studies using young and elderly male and female volunteers. Effects on particular aspects of cognitive function as well as effects on mood state are generally consistent with the common perception of caffeine as a compound that increases mental energy and performance. For example, using a double-blind and placebo-control protocol, Fine *et al.* (1994) reported that a single dose of 200 mg of caffeine improves visual vigilance in rested volunteers. Similar effects have been documented with doses equivalent to a single serving of a cola beverage (~ 40 mg) up to multiple cups of coffee (Lieberman *et al.* 1987). However, with a very high dose of caffeine (i.e., ~500 mg), cognitive performance was reported to decrease (Kaplan *et al.* 1997). This finding indicates that a dosage which is achievable via diet would be sufficient in order to procure the cognitive benefits of caffeine. Caffeine has also been shown to enhance cognitive performance such as reasoning and memory when an individual's mental ability decreases due to sleep deprivation (Penetar *et al.* 1993).

With respect to sports performance, the most consistent observation is that caffeine can increase the time to exhaustion during submaximal exercise bouts lasting approximately 30 to 60 minutes, though results are more inconsistent when activities of shorter duration are examined. Caffeine as an ergogenic substance has been evaluated for several decades. Despite an overwhelming agreement on caffeine's ability to improve endurance performance, the precise mechanism as to how this compound exerts its ergogenic effect still remains elusive. For years it has been postulated that caffeine causes glycogen sparing and therefore prolongs endurance performance. However, in terms of the exercise duration for which caffeine was found to be effective, it is unlikely that muscle glycogen would be depleted and thus serves as a limiting factor. In a recent study by Graham *et al.* (2000) who employed a muscle biopsy technique, it was found that the ingestion of caffeine at 5 mg kg^{-1} did not alter muscle glycogen utilization. Most studies have used a relatively small sample size (i.e., ~8 subjects), which may have reduced the statistical power needed to detect the difference. Nevertheless, by pooling together the studies conducted in the same laboratory but at different times and which involved a total of 37 subjects, Graham (2001) failed to observe a significant difference in muscle glycogen utilization between the caffeine and placebo conditions.

Another metabolic claim associated with caffeine is that it increases fat utilization. This notion was derived from early studies in which caffeine resulted in a larger decrease in muscle triglycerides concomitant with less utilization of muscle glycogen (Essig *et al.* 1980). It has been speculated that caffeine increases fat oxidation by augmenting lipolysis, a process stimulated by the release of epinephrine and norepinephrine. However, according to more recent studies by Raguso *et al.* (1996) and Graham *et al.* (2000), variables reflecting intracellular utilization of fatty acids such as fat oxidation and uptake of fatty acids by muscle remained unaffected by caffeine. These findings provide little support for the theory that caffeine increases fat oxidation.

Carnitine (L-carnitine)

L-carnitine, a substance found in relatively high quantities in meat, has received a lot of attention over the past 20 years. As a supplement it has been very popular among athletes, especially after rumors circulated that it helped the Italian national soccer team become world champions in 1982. L-carnitine can be synthesized from lysine and methionine, and synthesis occurs in the liver and kidneys. Therefore, even when dietary sources are insufficient, the body can produce enough from lysine and methionine to maintain a normal storage. As discussed in Chapter 9, carnitine functions as a carrier protein that helps transport long-chain fatty acids into the mitochondrial matrix so that they may be oxidized. In this context, carnitine is often regarded as a "fat burner." It is assumed that oral ingestion of carnitine increases the muscle carnitine concentration. This will then cause an increase in fat oxidation and a gradual loss of the body fat stores. However, several studies have shown that oral ingestion of carnitine up to 14 days produces no change in muscle carnitine concentration.

L-carnitine supplementation has also been thought to be ergogenic in improving endurance performance. This belief is based on the similar assumption mentioned earlier that oral ingestion of carnitine increases the total carnitine concentration in the muscle and that the increase in muscle carnitine increases the oxidation rate of plasma fatty acids and intramuscular triglycerides. This increased fat oxidation will in turn reduce muscle glycogen breakdown and postpone fatigue. However, the results of nearly all of the experimental trials have not revealed a positive influence on either fatty acid utilization or glycogen sparing, nor does carnitine supplementation delay fatigue (Heinonen 1996, Wagenmakers 1999). In addition, direct measurements of muscle following 14 days of carnitine supplementation failed to show increases in the muscle carnitine concentration (Barnett *et al.* 1994, Vukovich *et al.* 1994). It has been found that carnitine helps in preventing lactic acid from increasing via its effect on the maintenance of acetyl-CoA to CoA ratio (Bremer 1983). Nevertheless, Trappe *et al.* (1994) found that lactate accumulation, acid base balance, or performance in 5 100-yard swims with 2-minute rest intervals did not differ among competitive swimmers who consume 2 g of L-carnitine twice a day for 7 days and swimmers who consume the placebo.

L-carnitine also acts as a vasodilator in peripheral tissues, thus possibly enhancing regional blood flow and oxygen delivery. In one study, subjects took either L-carnitine supplements (3 g/day for 3 weeks) or an inert placebo to evaluate the effectiveness of L-carnitine supplementation on delayed onset of muscle soreness (DOMS) (Giamberardino *et al.* 1996). They then performed eccentric muscle actions to induce muscle soreness. Compared with placebo conditions, subjects who took the treatment experienced less post-exercise muscle pain and tissue damage as indicated by lower plasma-level creatine kinase. These findings suggest that the vasodilation property of L-carnitine may improve oxygen supply to injured tissue and promote clearance of muscle damage by-products, thus reducing DOMS.

Chromium

Chromium is a trace mineral present in foods such as brewer's yeast, cheese, broccoli, wheat germ, nuts, liver, apples with the skin on, asparagus, mushrooms, and egg yolks. As discussed in Chapter 6, chromium potentiates insulin action and insulin stimulates the glucose and amino acid uptake by muscle cells. The stimulated amino acid uptake is thought to increase protein synthesis and thus muscle mass. For this reason, chromium is considered ergogenic and helps athletes improve their strength and power. Chromium supplements are marketed mainly as chromium picolinate. Picolinate is derived from amino acid tryptophan and binds with chromium in order to enhance intestinal absorption of chromium. Chromium exists mainly as a positively charged ion (e.g., Cr^{+3}). Thus, combining with picolinate would decrease the potential interaction between chromium and other negatively charged substances in food such as phytates. Touted as a "muscle builder," chromium represents one of the largest-selling mineral supplements in the United States – second only to calcium.

The ergogenic impact of chromium supplementation was demonstrated in earlier studies in which college students as well as football players were given 200 μg of chromium picolinate or a placebo each day for 40 days while they were on a resistance training program (Evans 1989). It was found that those who took chromium supplementation gained significantly more lean body mass as compared to the control group, although lean body mass was estimated from skinfold thickness. However, later studies (Clancy *et al.* 1994, Hallmark *et al.* 1996, Hasten *et al.* 1992, Lukaski *et al.* 1996) which used more sophisticated techniques to determine body composition have not been able to confirm the results of Evans (1989). For example, in a study by Lukaski *et al.* (1996), chromium supplements in nearly the same amount as were used by Evans (1989) were given to a group of young men who were also in a resistance training program, and no change in body composition and strength were observed between the treatment and placebo groups. In another study by Clancy *et al.* (1994), football players received 200 μg of chromium picolinate each day for 9 weeks during strength training program. Here again, supplementation failed to independently affect percentage of body fat, lean body mass, and muscular strength. Clearly, the ergogenic benefits of chromium supplementation remain questionable.

Caution must be exercised in the use of chromium supplements. No studies have evaluated the safety of long-term supplementation with chromium picolinate or ergogenic efficacy of supplementation in individuals with less than optimal chromium status. Concerning the bioavailability of trace minerals in the diet, excessive dietary chromium can inhibit zinc and iron absorption. At the extreme, this could result in iron-deficient anemia, blunt the ability to train intensely, and negatively affect the performance of exercises that depend on a high level of oxygen supply. Based on laboratory studies of cultured cells, an accumulation of chromium picolinate in cells was shown to cause chromosome damage (Stearns *et al.* 1995), although this finding has yet to be demonstrated in humans.

Coenzyme Q_{10} (ubiquinone)

Coenzyme Q_{10} is often referred to as CoQ_{10} or ubiquinone. It is found primarily in meats, peanuts, and soybean oil. It functions as an integral component of the mitochondrion's electron transport system, and therefore plays an important role in oxidative phosphorylation. This lipid-soluble natural component of all cells exists in high concentrations within myocardial tissues. CoQ_{10} has been used clinically to treat cardiovascular diseases and promote recovery from cardiac surgery owing to its antioxidant properties

that promote scavenging of free radicals (Vasankari *et al.* 1997). Due to its positive effect on oxygen uptake and exercise performance in cardiac patients, CoQ_{10} has been considered as an ergogenic aid for endurance performance. The rationale behind this consideration is that supplementation could increase the flux of electron through the respiratory chain and thus augment aerobic resynthesis of ATP.

Based on the current literature, it appears that supplementation of CoQ_{10} increases serum CoQ_{10} levels, but it does not improve aerobic capacity and endurance performance (Braun *et al.* 1991, Snider *et al.* 1992, Zuliani *et al.* 1989). For example, a study which provided male cyclists with 100 mg per day of ubiquinone for 8 weeks failed to demonstrate improvements in cycling performance, VO_2max, and lipid peroxidation (Braun *et al.* 1991). Likewise, when triathlons were given 100 mg of ubiquinone in a daily supplement that also contained vitamin E, inosine, and cytochrome c for 4 weeks, no differences in endurance performance and blood glucose, lactate, and free fatty acid concentrations at exhaustion were observed between treatment and placebo condition (Snider *et al.* 1992). In a study in which tissue CoQ_{10} level was measured, Svensson *et al.* (1999) reported that ingestion of 120 mg of CoQ_{10} daily for 20 days resulted in marked increases in plasma CoQ_{10} concentration. However, the muscle CoQ_{10} levels as well as other cellular activities such as lipid peroxidation and mitochondrial function remained unaltered. This finding may explain why most studies failed to demonstrate ergogenic values of CoQ_{10} supplementation despite the fact that supplementation increased plasma CoQ_{10} concentration.

Creatine

Creatine is a nitrogen-containing molecule produced in the liver, kidneys, and pancreas. Because creatine can be synthesized internally, it is not considered an essential nutrient. In normal, healthy individuals, creatine is synthesized at about 1 to 2 grams per day. At approximately the same rate, creatine is broken down into creatinine and excreted in the urine. Under normal circumstances, the degradation of creatine is matched by its synthesis. In strength and power athletes, however, the rate of creatine breakdown is expected to be much higher. Therefore, adequate dietary creatine becomes important for obtaining the required amounts of this compound. Because creatine is found in meat products such as meat, poultry, and fish, vegetarians are at a distinct disadvantage in obtaining ready sources of exogenous creatine.

Creatine is synthesized from arginine, glycine, and methionine. Once synthesized, creatine is transported via the blood from the liver and kidneys to the muscle. Muscle takes up creatine against the concentration gradient by an active transport process. A 70-kg (154 lb) man may have a creatine pool of approximately 120 grams or a little more than 1/4 lb, 95 percent of which is in muscle tissues. Of course, skeletal muscle represents the largest reservoir of creatine among three types of muscle tissue (e.g., skeletal, smooth, and cardiac muscle tissue). About 40 percent of the total exists as free creatine; the remainder combines readily with phosphate to form phosphocreatine (PCr). Type II or fast-twitch muscle fibers store about 30 percent more creatine than type I fibers.

As discussed in Chapter 8, the body has limited storage of ATP and during maximal exercise the ATP stores can only provide energy for several seconds. With ATP falling by 30 percent, the muscle fatigues (Hultman *et al.* 1991). PCr serves as the "energy reservoir" to provide rapid phosphate-bond energy to resynthesize ATP and to maintain ATP concentration close to resting levels. In doing so, the maximal work of muscle may be sustained for a longer period of time. This process occurs during the first few seconds of high-intensity exercise, and thus allows time for other more sustained glycogen breakdown and glycolysis to speed up to the required rate. Another important function of PCr

is that it helps with buffering capacity for hydrogen ions. Hydrogen ions are used during ATP regeneration. Therefore, as PCr continues to be used to phosphorylate ADP to ATP, fewer free hydrogen ions will be available. The increased availability of PCr also lessens reliance on energy transfer from anaerobic glycolysis with subsequent lactate formation.

Creatine became a popular supplement following the 1992 Olympics in Barcelona. For example, gold medal winners Linford Christie in the men's 100-meter dash and Sally Gunnell in the women's 400-meter hurdles supposedly used creatine supplements. By the Olympics game in Atlanta in 1996, approximately 80 percent of all athletes were using creatine. Since then, creatine has become one of the most popular ergogenic aids used by athletes worldwide. Creatine is usually marketed in the form of creatine monohydrate. Most studies used a creatine loading regimen of 20 to 25 g/day in 4 portions of 5 to 6 g each given at different times of the day for 5 to 7 days. This is because a similar loading regimen has been shown to increase the muscle creatine concentration by 20 percent (Hultman *et al.* 1996). Hultman *et al.* (1999) also found that a subsequent dose of 2 g/day was enough to maintain the high total creatine concentration for 35 days, whereas stopping creatine supplementation after 6 days caused a slow and gradual decline of the creatine concentration in muscle. Another approach suggested by this same research group is to take creatine at a constant dose of 3 g/day, but in order to achieve a similar total muscle creatine concentration one would need to maintain daily consumption for about a month. It was also found that creatine taken in conjunction with carbohydrate would produce greater creatine retention compared with creatine alone (Green *et al.* 1996). It is considered that by adding carbohydrate the supplement would trigger a greater release of insulin, which would then increase tissue uptake of creatine.

Research regarding the effect of creatine supplementation on performance in humans began in the early 1990s. Since then it has quickly proliferated up until the present. Of the studies published, a majority have been in favor of this ergogenic aid. In general, oral supplements of creatine monohydrate at 20 to 25 grams per day increase muscle creatine and performance of both men and women in intense exercise, particularly repeated intensity of muscular effort. Even a daily dose as low as 6 grams for 5 days elicits improvement in repeated power performance. The exercises used in the studies that observed the ergogenic effect of creatine supplements are mainly sprint or repeated sprint events that involve running, cycling, and swimming. Supplementation has not been shown to improve endurance performance, but if a competition involves sprinting such as cycling breakaway or final running sprints, creatine may be of benefit. It has been postulated that creatine could facilitate aerobic energy production and enhance endurance performance because creatine PCr provides a shuttle system for the transfer of high-energy phosphate groups from mitochondria where ATP is produced to contractile myofibrils where energy is used for making muscle contraction. However, this theory remains to be tested. Endurance athletes must also consider the potential weight gain that may accompany creatine supplementation.

Several studies have reported an increase in total body mass and lean body mass and a corresponding decrease in percentage of body fat. It is likely that creatine causes water retention in skeletal muscle cells due to an increase in the intracellular osmolarity of the muscle cells. Many believe that the creatine-induced increase in water retention leads to increased protein synthesis, although in the short term (i.e., 5 to 6 days), the increase in protein synthesis may not be of great magnitude. Such favorable change in body composition has also been attributed to a high quality of training due to creatine supplementation. The increase in body mass may be beneficial. However, in sports that involve weight-bearing activities, such as running and gymnastics, the weight gain caused by creatine supplementation could have a negative impact upon performance. Figure 11.1

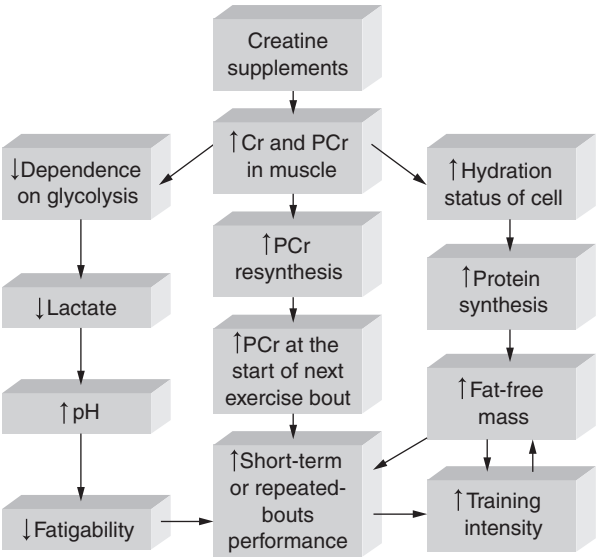


Figure 11.1 Possible mechanisms of how creatine supplementation works in improving performance and body composition

illustrates the proposed mechanisms demonstrating how elevating intramuscular creatine and phosphocreatine enhances intense, short-term performance and improves body composition.

DHEA and androstenedione

Dehydroepiandrosterone (DHEA) and its sulfated metabolite (DHEAS) are produced in the body by the adrenal glands. Both DHEA and DHEAS circulate to peripheral tissues where they are converted into androgens (including testosterone) and/or estrogen (Figure 11.2). DHEA is derived from cholesterol and may be converted into androstenedione and then into testosterone. The ability of tissue to convert DHEA into androstenedione, into testosterone, and/or estrogen relies on the presence of steroidogenic and/or metabolizing enzyme systems. Both androstenedione and testosterone may be converted into estrogen via aromatase. Many tissues produce these converting enzymes, including gonads (testes and ovaries), liver, kidneys, and adipose tissue. This allows the conversion of both hormones to be regulated at tissue level. Skeletal muscle lacks the ability to convert androstenedione into testosterone.

Body levels of DHEA are high in young adulthood, with the peak production occurring between the ages of 18 and 25, and gradually decrease with aging. In contrast to the glucocorticoid and mineralocorticoid (i.e., aldosterone) adrenal steroids whose plasma levels remain relatively high with aging, a long and slow decline in DHEA begins after the age of 30. This has fueled speculation that plasma DHEA may play a role in biological aging and its related dysfunctions or diseases. As such, it is believed that supplementing with DHEA blunts the negative effects of aging by raising plasma levels of DHEA to more "youthful" concentrations (Percheron *et al.* 2003). Among the popular claims for using DHEA include (1) blunts aging, (2) facilitates weight loss, (3) boosts immune function, (4) protects heart, and (5) increases muscle mass.

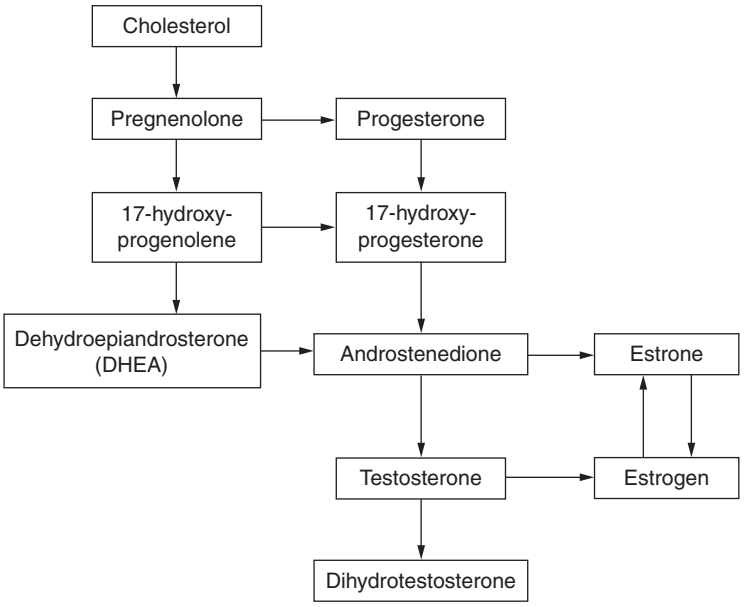


Figure 11.2 Metabolic pathways for producing DHEA and androstenedione

Treatment with DHEA has been shown to have beneficial effects in preventing diseases, such as cancers, atherosclerosis, viral infections, obesity and diabetes, and enhancing immune function and life span, but results came from studies that used rodents. Scientists have argued that the findings from research on rats and mice who produce little, if any, DHEA, do not necessarily apply to healthy human. Results from human studies are mixed. Evidence that supports the use of DHEA came from the cross-sectional comparisons relating levels of DHEA to risk of death from heart disease. However, it was found that a high DHEA level conferred cardio-protective effects only in men, not in women. In the context of ergogenic aid, the DHEA-induced improvement in body composition, immune function, and muscular strength have been reported in studies involving middle aged and elderly adults (Villareal and Holloszy 2006). However, research in young men who were given DHEA at comparable doses failed to demonstrate any positive effect on serum testosterone, lean body mass and muscular strength (Percheron *et al.* 2003, Wallace *et al.* 1999). Therefore, despite its popularity among exercise enthusiasts, no data exist concerning ergogenic effects of DHEA supplements on young adults. Use of DHEA supplements for the elderly seems to be more promising, but its safety remains to be further investigated.

Androstenedione and related compounds such as androstenediol and norandrostenediol function similarly to DHEA. Androstenedione is an intermediate or precursor hormone between DHEA and testosterone (Figure 11.2). Normally produced by the adrenal glands and gonads, it converts into testosterone by 17β-hydroxysteroid dehydrogenase found in diverse tissues. Androstenedione also serves as an estrogen precursor. Originally developed by East Germany in the 1970s to enhance performance of their elite athletes, androstenedione was first made commercially available in the United States in 1996. Androstenedione received considerable notoriety during the 1998 baseball season when Mark McGwire, who established a home run record at that time,

acknowledged using this supplement. Subsequently, androstenedione-related products flooded the marketplace for resistance-trained individuals, even though no reputable research was available supporting its beneficial effects.

It remains controversial as to whether androstenedione supplementation can increase the level of testosterone in the blood. Leder *et al.* (2000) observed that although a week-long supplementation of androstenedione at 100 mg per day did not alter serum testosterone levels, at 300 mg it elevated testosterone levels by 24 percent. In this study, however, no performance was measured. On the other hand, by supplementing subjects with androstenedione at 300 mg/day for 8 weeks, King *et al.* (1999) failed to observe any significant effects on serum testosterone, body fat, lean body mass, muscle fiber diameters, or muscle strength, although serum androstenedione levels increased 100 percent in the treatment group. Of particular interest is that they noted a significant increase in serum estradiol and estrogen concentrations, suggesting an increased aromatization of ingested androstenedione to estrogen instead of testosterone. Based on these findings, it appears that androstenedione supplementation does not predictably elevate serum testosterone levels. Even though some researchers found significant increases of testosterone levels in the blood, these increases were not accompanied by favorable changes in protein synthesis, muscle mass, or strength.

Concerns exist about the effect of long-term DHEA and androstenedione supplementation on body function and overall health. Converting these anabolic hormone precursors into potent androgens like testosterone in the body promotes facial hair growth in females and alters normal menstrual function. As with exogenous anabolic steroids, DHEA or androstenedione through supplementation may stimulate the growth of the prostate gland that can lead to a tumor. They may also accelerate the growth of cancer cells if cancer is present. In addition, a lowering of HDL cholesterol has been reported in a few studies (Broeder *et al.* 2000, Brown *et al.* 2000). A low level of HDL cholesterol is considered a risk factor for heart disease. The IOC and NCAA have placed both DHEA and androstenedione on their banned substance list at zero-tolerance level. Supplementation of these substances may influence the ratio of testosterone to epitestosterone (T/E), which is used to screen for steroid doping by organizations such as the IOC and NCAA.

Ephedrine

Ephedrine is a sympathomimetic agent which is structurally related to catecholamine. It is found in several species of the plant Ephedra and has been used for thousands of years as a herbal medicine. Ephedra, which is also called Ma-Huang, is the dry stem of a plant that is indigenous to China, Pakistan, and northwestern India. While ephedrine occurs naturally in some botanicals, it can also be synthetically derived. Ephedrine is widely available in over-the-counter remedies for nasal congestion and hay fever. It has also been used as a central stimulant to treat depression and sleep disorders.

Ephedrine is a potent chemical stimulant with a variety of peripheral and central effects. It acts by enhancing the release of norepinephrine from sympathetic neurons and is also a potent β-adrenergic agonist. In this regard, ephedrine has been known for its effect of stimulating bronchodilation, increasing heart rate and cardiac contraction, and augmenting energy expenditure and fat oxidation. Ephedrine also functions to suppress appetite and food intake through adrenergic pathways in the hypothalamus.

Ephedrine is recognized as an anti-obesity drug due mainly to its stimulating effect on the sympathetic nervous system. Ephedrine's potential for weight loss was first reported in 1972. It was noted that asthmatic patients being treated with a compound containing ephedrine, caffeine, and phenobarbitol experienced unintentional weight loss. This unexpected discovery led to a series of investigations aimed to authenticate whether ephedrine

is indeed effective in facilitating weight loss and whether it warrants safety concerns, despite its efficacy. Among the early studies in which ephedrine was the only substance tested, results of energy expenditure and weight loss are controversial. Astrup *et al.* (1985) noticed a sizable increase in resting oxygen consumption and a significant reduction in body weight in obese women who were treated with ephedrine at 60 mg per day. However, Pasquali *et al.* (1987a) found that administering ephedrine at a dose of 75 or 150 mg per day produced essentially no effect compared to the placebo condition in obese individuals. In this study, side-effects such as agitation, insomnia, headache, palpitation, giddiness, tremor, and constipation were reported in the group treated with 150 mg per day. This same research group, however, observed that when ephedrine was given at a dose of 150 mg per day in conjunction with a more stringent hypocaloric diet (~ 1000 kcal per day), obese women did experience significant weight loss (Pasquali *et al.* 1987b). It appears that the efficacy is questionable especially when ephedrine is given alone.

Ephedrine has also been promoted as a performance-enhancing or ergogenic aid. However, most studies have not demonstrated any kind of improvement in athletic performance following ingestion of ephedrine alone at a dose generally considered safe, i.e., <120 mg. DeMeersman *et al.* (1987) found no significant effects of ephedrine administrated in a dose of 40 mg on sustained aerobic exercise. Swain *et al.* (1997) also failed to observe increases in VO_2max and endurance time to exhaustion following consumption of pseudoephedrine at doses of 1 or 2 mg kg^{-1}. Ephedrine also seems to be ineffective with respect to its impact on anaerobic performance. Chu *et al.* (2002) reported that ingestion of pseudoephedrine of 120 mg two hours before testing did not improve muscular strength as measured by intermittent isometric contraction and anaerobic performance as measured by the Wingate cycling test comprising 30 seconds of maximal cycling against a predetermined resistance. It may be argued that a threshold dosage level exists for the ergogenic effects of ephedrine to manifest, as the peak weight-lifting performance was improved with taking a high dose (180 mg) of pseudoephedrine (Gill *et al.* 2000). Nevertheless, in a more recent study in which subjects were fed 240 mg of pseudoephedrine, Chester *et al.* (2003) failed to demonstrate an ergogenic effect, although the testing protocol of this study involved aerobic rather than anaerobic performance.

More recently, a great deal of research has also been undertaken to investigate the ergogenic effect of ephedrine in combination with caffeine. There is a consensus that the combined use of ephedrine and caffeine is of greater ergogenic benefit than each compound used alone. For instance, Bell *et al.* (2001) demonstrated a significant increase in power output during a 30-second Wingate test following the ingestion of ephedrine (1 mg kg^{-1}) alone and in combination with caffeine (5 mg kg^{-1}) as compared with caffeine alone and placebo. Using the same treatment paradigm, this research group also found a significant reduction in time spent during a 10 k race following ingestion of ephedrine (0.8 mg kg^{-1}) alone and in combination with caffeine (4 mg kg^{-1}) as compared with caffeine alone and placebo (Bell *et al.* 2002). The mechanism responsible for the performance advantages of this combined approach is unclear. It may be related to the hypothesis that caffeine serves to prolong the ephedrine-induced adrenergic effect. It should be noted that the amount of ephedrine used by Bell *et al.* is about twice as potent as pseudoephedrine used in many early studies. This may have also contributed to positive findings shown by most of Bell's publications.

The most common side-effects for ephedrine are agitation, insomnia, headache, palpitations, dizziness, tremor, and constipation, many of which are quite similar to those associated with sympathomimetic drugs such as phentermine and fenfluramine. Ephedrine can also trigger cardiovascular events such as tachycardia, cardiac arrhythmias, angina, and vasoconstriction with hypertension, although these cardiovascular

side-effects have been found to be relatively infrequent and tend to diminish on repeated dosing. Because of this, ephedrine and other sympathomimetics are banned by IOC and other organizations such as NCAA and NFL.

Glutamine

Glutamine is a naturally occurring nonessential amino acid and the most abundant amino acid in human muscle and plasma. It is important as a constituent of protein and as a means of nitrogen transport between tissues. It is also important in acid-base regulation and as a precursor of the antioxidant glutathione. Its alleged ergogenic effects with glutamine supplementation may be classified as anabolic and protective. Glutamine supplementation is considered to promote a positive protein balance by enhancing protein synthesis and counteracts the decline in protein synthesis. This claim, however, remains to be substantiated. In a study that used female rats, infusing glutamine was found to inhibit the down-regulation of myosin synthesis and atrophy. Nevertheless, several human studies have not been able to confirm this anabolic effect. For example, Zachwieja *et al.* (2000) infused an amino acid mixture with and without glutamine directly into the blood of male and female subjects for several hours while estimating the rate of muscle protein synthesis. Although protein synthesis was enhanced by the amino acid infusion, there was no additional enhancement with the mixture that included glutamine. In another study in which a group of young adults were given glutamine supplement at 0.9 g/kg of lean body mass daily while also undergoing resistance training for 6 weeks, glutamine supplementation had no significant effect on muscle performance, body composition, or muscle protein degradation indices (Candow *et al.* 2001). Data also indicate that glutamine supplementation promotes muscle glycogen synthesis during recovery, perhaps by serving as a gluconeogenic substrate in the liver (Varnier *et al.* 1995). However, the practical application of these findings for promoting glycogen replenishment following exercise requires further research.

The protective aspect of glutamine concerns its use as an energy fuel for nucleotide synthesis by diseases fighting cells, particularly the lymphocytes and macrophages that defend against infection. Injury, burns, surgery, and endurance exercise lower glutamine levels in plasma and skeletal muscle due to an increase demand by the liver, kidneys, gut, and immune system. It has been suggested that a lowered plasma glutamine concentration contributes, at least in part, to the immune suppression that occurs with extreme physical stress (Smith and Norris 2000). For example, prolonged exercise at 50 and 70 percent VO_2max causes a 10 to 30 percent fall in plasma glutamine concentration that may last for several hours during recovery. This fall in plasma glutamine coincides with the time period during which athletes are more susceptible to infections following prolonged exercise. Will glutamine supplementation reverse this stress-related perturbation in immune function? Although supplementing glutamine has been presumed to be able to prevent the impairment of immune function after exhaustive exercise, insufficient data exist to substantiate this claim. In fact, most recent studies have failed to demonstrate any effect of glutamine supplementation on preserving immune function following exhaustive exercise. The supplementation appears to prevent the exercise-induced fall in plasma glutamine levels, but does not prevent the fall in lymphocyte proliferation and lymphocyte-activated killer cell activity (Castell *et al.* 1996, Gleeson and Bishop 2000).

Glycerol

Glycerol is a component of the triglyceride molecule and an important constituent of the cell membrane. This three-carbon molecule can be a substrate for gluconeogenesis

and, as such, could provide a fuel during exercise. We ingest a fairly large amount of glycerol as part of triglycerides or dietary fats on a daily basis. Glycerol is also released into the bloodstream from lipolysis that breaks down triglycerides into glycerol and three free fatty acids. Thus, during exercise, when lipolysis is stimulated, plasma glycerol concentrations will increase. Glycerol has been touted as a possible ergogenic aid for two reasons. First, it is a substrate for gluconeogenesis and may thus become a necessary resource for glucose production during prolonged exercise. Second, supplemented glycerol is distributed evenly throughout body fluid and may provide an osmotic influence that could help an athlete hyperhydrate prior to competition in a warmer environment.

The studies that investigated the efficacy of glycerol as a fuel have not been positive. In well-controlled research, glycerol feedings did not prevent either hypoglycemia or muscle glycogen depletion. In addition, the contribution of glycerol to overall energy expenditure was found to be relatively small. Glycerol cannot be oxidized directly in very large amounts in the muscle. Therefore, glycerol must be converted into a glucose molecule in gluconeogenesis before being used as a fuel. Unfortunately, the rate at which the human liver converts glycerol into glucose is not sufficiently rapid to be an effective energy source during prolonged strenuous exercise.

Glycerol as a hyperhydrating agent has received a great deal of attention. When consumed with one to two liters of water, glycerol facilitates water absorption from the intestine and causes extracellular fluid retention, mainly in the plasma fluid compartment. This action may occur because glycerol moves through various tissues at a relatively slow rate; this then creates an osmotic effect that draws fluid into extracellular space including plasma. The hyperhydration effect of glycerol supplementation reduces overall heat stress during exercise as reflected by increased sweating rates. This lowers heart rate and body temperature during exercise and enhances endurance performance under heat stress (Lyons *et al.* 1990). Several studies have found no effect of glycerol on thermoregulation (Inder *et al.* 1998, Latzka *et al.* 1997, 1998). However, these studies used a volume of water (i.e., 500 ml) that may have been too small. It is recommended that the ingestion of 1 g/kg body weight of glycerol with one to two liters of water would be effective in protecting against heat stress. Glycerol supplementation may have a positive effect on hyperhydration. However, users should be aware that glycerol has significant side-effects, including nausea, dizziness, headache, bloating, and cramping (Wagner 1999).

Hydroxy citric acid (HCA)

Hydroxy citric acid (HCA) is a derivative of citric acid found in a variety of tropical plants, including garcinia cambogia and hibiscus subdariffa. HCA is a competitive inhibitor of ATP citrate lyase, which converts citrate into oxaloacetate and acetyl-CoA. The reverse of this conversion is a step in the Krebs cycle that promotes fat oxidation. HCA is usually marketed as a weight loss supplement either alone or in combination with other supplements. Research has suggested that HCA causes weight loss by competitively inhibiting the enzyme **ATP citrate lyase** (Onakpoya *et al.* 2011). This enzyme catalyzes reactions of fatty acid biosynthesis from carbohydrate. Therefore, with the inhibition of ATP citrate lyase, a loss of body fat is expected. HCA has also been reported to increase the release or availability of serotonin in the brain, thereby leading to appetite suppression (Toromanyan *et al.* 2007).

Although some studies using mice suggest that HCA supplementation may trigger weight loss and enhance endurance performance, human studies do not support such a claim. Using sedentary males, Kriketos *et al.* (1999) reported no significant effect of ingesting HCA at 3 g/day for 3 days on fat metabolism and energy expenditure either at rest or during moderately intensive exercise. When giving endurance-trained cyclists

HCA in a higher dose (3.1 ml/kg of a 19 percent HCA solution) twice before and during 2 hours of cycling at 50 percent VO_2max, van Loon *et al.* (2000) also observed no increase in total fat oxidation. Given that HCA supplementation does not modify fat utilization during exercise, its ergogenic effect on body composition and endurance performance seems highly unlikely.

β-hydroxy-β-methylbutyrate (HMB)

***β*-hydroxy-*β*-methylbutyrate** (HMB) is a metabolite of the essential amino acid leucine. Depending on the amount of HMB contained in foods, the body synthesizes between 0.2 to 0.4 g/day, of which a very small percentage (i.e., ~5 to 10 percent) is derived from dietary leucine catabolism. Foods rich in HMB are red meats, asparagus, cauliflower, catfish, and grapefruit. HMB is available to consumers as an independent supplement or as an ingredient of combination supplement or sport food. Because of its nitrogen-retaining effect, many resistance-trained athletes supplement directly with HMB to prevent or reduce muscle damage and to suppress proteolysis or protein degradation associated with intense physical effort. The assumption that HMB supplementation would have a positive impact on muscle metabolism may be based on *in vitro* animal studies in which researchers noted a marked decrease in protein breakdown and a slight increase in protein synthesis in the muscle tissue of rats and chicks exposed to HMB.

The number of studies to test the efficacy of HMB as an ergogenic aid is rapidly growing. However, findings remain divided at present. In those studies that supported the use of HMB as an ergogenic aid, a decrease in muscle damage and protein synthesis was observed along with an increase in strength performance following consumption of HMB supplements. For example, in one such supportive study, Nissen *et al.* (1996) examined the ergogenic effect of HMB using two separate randomized trials. In trial 1, authors provided 1.5 or 3 g of HMB daily to untrained males for 3 weeks, during which subjects also participated in a resistance training program 3 days a week for 3 weeks. In trial 2, subjects consumed either 0 or 3 g of HMB per day and weight lifted for 2 to 3 hours, 6 days per week for 7 weeks. It was found from trial 1 that HMB supplementation depressed the exercise-induced rise in muscle proteolysis as reflected in urine 3-methylhistidine (3-MH) and plasma creatine kinase levels during the first 2 weeks of training. 3-MH is a marker of contractile protein breakdown, and creatine kinase is an indicator of muscle damage. In addition, this group lifted more total weight than the placebo group during each training week, with the greatest effect in the group receiving the largest dose of HMB supplement. With regard to trial 2, it was found that subjects who received the HMB supplement had higher fat-free mass than the un-supplemented subjects at 2 and 4 to 6 weeks of training.

Not all research shows beneficial effects of HMB supplementation with resistance training. For example, a study involving collegiate football players taking 3 g of HMB daily whose strength training program was monitored by their strength and conditioning coach failed to demonstrate a positive effect on strength and body composition (Ransone *et al.* 2003). One of the hypotheses is that HMB supplementation would reduce muscle damage and suppress protein degradation associated with intense training. Nevertheless, Kreider *et al.* (1999) reported that 28 d of HMB supplementation at a dose of 3 or 6 g per day during resistance training did not reduce catabolism in experienced resistance-trained males. Paddon-Jones *et al.* (2001) also found that HMB supplementation at a similar dose did not reduce the symptoms associated with muscle soreness induced by eccentric contraction. There appears to be some evidence to support the use of HMB as an ergogenic aid. However, more studies are needed, especially to examine its efficacy among trained individuals.

Inosine

Inosine is a nucleoside, a purine base comparable to adenine, which is one of the structural components of ATP. It is found naturally in brewer's yeast and organ meats. Inosine is not considered an essential nutrient. The body synthesizes inosine from precursor amino acids and glucose. Inosine in the form of nucleotide inosine monohydrate (IMP) is used to make adenine monophosphate (AMP), which in turn can be phosphorylated to the high-energy phosphate compound ATP. Strength and power athletes supplement with inosine believing that it increases ATP stores, thereby improving training quality and competitive performance. Inosine is also thought to improve endurance performance. It has also been theorized that inosine participates in the formation of 2,3-diphosphoglycerate (2,3-DPG), a substance in red blood cells that facilitates the release of oxygen from hemoglobin to the tissue. Among other claims on inosine include its role in (1) stimulating insulin release to enhance glucose delivery, (2) augmenting cardiac contractility, and (3) acting as a vasodilating agent. It is mainly due to these theoretical considerations that inosine has been extolled as an ergogenic supplement to improve both anaerobic and aerobic performance.

Objective data do not support the ergogenic role of inosine supplementation in improving either aerobic or anaerobic performance. In fact, it has been suggested that this supplement may have **ergolytic** effects under certain conditions. In one carefully conducted study, trained men and women were administered 6 g/day of inosine or placebo for 2 days, but no change was observed in 3-mile treadmill run time, VO_2max, or perceived exertion (Williams *et al.* 1990). After a 30-minute break, subjects performed another run in which speed was kept constant but the treadmill grade increased gradually. It was found that time to exhaustion in this run was actually longer during the placebo trial, suggesting a possible negative effect of inosine supplementation. In another study, male competitive cyclists received either a placebo or a 5 g/day of oral inosine supplement for 5 days (Starling *et al.* 1996). They then performed a Wingate bicycle test, a 30-minute self-paced bicycle endurance test, and a constant load, supramaximal cycling sprint to fatigue. No significant differences occurred in any of the criterion variables in terms of performance as well as blood 2,3-DPG concentrations between placebo and treatment conditions. Similarly, this study also showed that cyclists fatigued nearly 10 percent faster on the supramaximal sprint test when they consumed inosine than without it, again indicating that inosine may be detrimental to performance.

Nitric oxide (NO)

Nitric oxide (NO) is a powerful messenger molecule in the body. NO is formed from L-arginine in the endothelial cells that line the blood-vessels. Due to the relatively small size of NO, it is able to diffuse freely across membranes where it can act as a powerful vasodilator to increase blood flow to muscle. Long-known pharmaceuticals such as nitroglycerine and amyl nitrite were found to be precursors to NO more than a century after their first use in medicine. In addition to its generation through oxidation of L-arginine, NO can also be formed from reducing nitrate (NO_3^-) and nitrite (NO_2^-). Bodily storage of nitrate and nitrite can be increased through diet, particularly through the consumption of green leafy vegetables such as lettuce, spinach, celery, cress, and beetroot.

It is considered that NO can modulate skeletal muscle function through its role in the regulation of blood flow, contractility, glucose and calcium homeostasis, and mitochondrial respiration and biogenesis (Stamler and Meissner 2001). However, the most prevailing evidence concerning NO relates to its ability to reduce oxygen cost of exercise and improve exercise tolerance. By feeding subjects with sodium nitrate (0.1 mmol/kg)

or a placebo for 3 days, Larsen *et al.* (2007) observed a reduction in oxygen uptake during exercise and a committed improvement in exercise efficiency (calculated as the work output per unit energy expended). This finding was later confirmed by Bailey *et al.* (2009) who used a natural nitrate-rich dietary source, beetroot juice, as the nitrate supplement, which contained 5.6 mmol nitrate. An improvement in muscle efficiency would be expected to enable a greater workload accomplished for the same energy cost. In theory, this should translate into improved performance assuming that other factors stay the same. It has been further speculated that this more efficient use of oxygen may be accomplished by improving blood flow to contracting muscle, the oxidation-phosphorylation coupling process in mitochondria, and/or Ca_2^+-related actin–myosin interaction in muscle cells (Jones 2014) (Figure 11.3). It must be noted that research regarding nitrate supplementation is in its early stages. Not all studies have shown similar results despite some promising findings that tend to support the role which NO plays in enhancing muscle efficiency and oxygenation.

Phosphate

Although it is uncommon, some athletes have tried to enhance performance by ingesting gram amounts of phosphate shortly before strenuous training or competition. This practice is called **phosphate loading**. Phosphate and phosphorus are often used interchangeably. Technically, phosphorus is an element (P), whereas phosphate is a molecular anion (PO_{4-}^{3}), part of phosphoric acid (H_3PO_4). Phosphate is a component of high-energy compounds, such as ATP and PCr, as well as 2,3-DPG, a molecule that facilitates oxygen release from hemoglobin for use by body tissues. Therefore, it has been postulated that phosphate supplementation may increase ATP synthesis and improve oxygen extraction in muscle cells because of elevations of 2,3-DPG in erythrocytes.

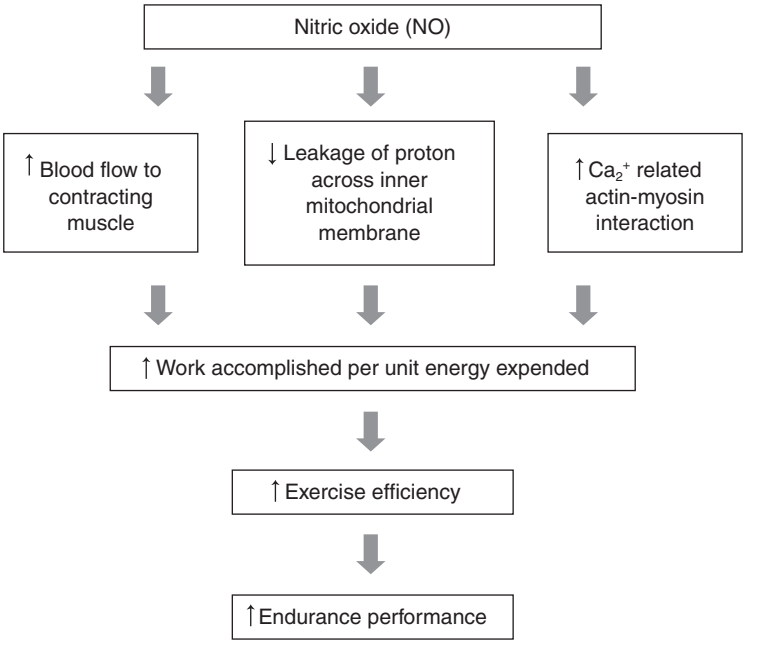


Figure 11.3 Possible mechanisms of how nitric oxide (NO) improves exercise performance

Despite these appealing rationales, the ergogenic benefits with phosphate loading have not been consistently demonstrated. Some studies show improvement in VO_2max, anaerobic thresholds, and endurance performance and/or decreased lactate concentration at submaximal workload (Cade *et al.* 1984, Kreider *et al.* 1990, 1992, Stewart *et al.* 1990), while others failed to do so (Bredle *et al.* 1988, Duffy and Conlee 1986, Galloway *et al.* 1996, Mannix *et al.* 1990). The inconsistencies in these findings may be related to the differences in the experimental protocol, i.e., dosage and duration of supplementation, type of subjects, exercise mode and intensity, and pre-test diets. In addition, most studies used very small numbers of subjects, which can make relatively minor changes in exercise performance difficult to detect.

At present, little reliable scientific evidence exists to recommend exogenous phosphate as an ergogenic aid. On the negative side, chronic phosphate loading can alter calcium-to-phosphate ratio, thereby affecting the rigidity of bones. In addition, excess plasma phosphate can stimulate the secretion of parathyroid hormone. Excessive production of this hormone increases the release of calcium from bones, causing loss of bone mass.

Synephrine

Synephrine, or, more specifically, p-synephrine, is an extract from the bitter or sour orange. This substance is typically included in weight loss products owing to its purported thermogenic effect. Many ephedra-free dietary supplements marketed for weight loss contain synephrine, along with other stimulants such as caffeine. Synephrine is structurally similar to ephedrine, and has been marked as a safe alternative to ephedra. Synephrine is a dietary supplement in the United States, but is classified as a drug in Europe. It has been previously found that p-synephrine induces an increase in basal metabolic rate (Gougeon *et al.* 2005) and lipolysis by activation of the β_3 adrenergic receptor (Stohs *et al.* 2011), which ultimately enhance body weight loss in weight management programs (Stohs *et al.* 2012).

P-synephrine is also consumed in the sports setting as an ergogenic supplement, although the existing evidence regarding its effectiveness in increasing physical performance is scarce and inclusive. No effects on performance in a squat jump, a countermovement jump, a 15-s repeated jump test as well as 60-m and 100-m simulated sprints were reported following an ingestion of p-synephrine in 3 mg/kg (Gutiérrez-Hellín *et al.* 2016). However, when subjects were fed 100 mg of p-synephrine plus 100 mg of caffeine, increases in mean power and velocity of squat performance were noted (Ratamess *et al.* 2016). In this latter study, it is difficult to associate performance enhancement with p-synephrine because caffeine by itself is a well-recognized ergogenic aid.

Whey and casein

Both **whey** and **casein** are derived from milk proteins as part of the cheese-making process. They are among the most popular protein supplements sold in powder format. Whey protein is acid soluble and is thus digested quickly and results in a pronounced aminoacidemia. Whey is a faster-acting protein. It reaches the bloodstream more quickly and elevates blood amino acid levels much higher than casein. It also has more leucine, which benefits muscle growth. Casein is slower to reach the bloodstream, but stays in the bloodstream much longer than whey. Research has demonstrated that whey supplementation induces a transient rise in protein synthesis at rest. Conversely, casein has a modest effect on protein synthesis, but instead inhibits protein breakdown.

In a study that compared whey, casein, and soy proteins, Tang *et al.* (2009) demonstrated that the consumption of whey hydrolysate (a pre-digested form) stimulated skeletal muscle synthesis to a greater extent than either casein or soy, both at rest and after resistance exercise. Despite its more profound effect on protein synthesis, the benefits of whey protein after exercise are generally short-lived. To examine the effect of ingestion rate of protein on postprandial protein synthesis, Dangin *et al.* (2001) found that 30 grams of whey protein provided in a sequence of 13 small meals given every 20 minutes was superior for muscle anabolism compared to a single meal of whey or casein. Based on this study, it appears that a post-workout whey protein shake should be followed by a protein-rich meal consumed shortly after the initial whey supplementation. Since whey rapidly increases protein synthesis and casein blocks protein breakdown, a combination of both is ideal. To have a sustained benefit on protein balance, one may consume a combination of whey and casein (~20 grams) one hour before and immediately after exercise. Casein is considered an ideal protein to consume before bed due to its long-lasting effect on muscle anabolism.

Summary

- Ergogenic is defined as increasing work or the potential to do work. Ergogenic aids consist of substances or procedures that improve physical work capacity, physiological function, or athletic performance. An ergogenic aid does not need to be nutritional or pharmacological; it can also be mechanical, psychological, or physiological.
- In contrast to prescription drugs which are carefully regulated, nutrition supplements and ergogenic aids receive very little government oversight, and manufacturers and retailers have enormous freedom in making claims to promote the product.
- All ergogenic aids need to be critically evaluated. Often, a "placebo effect," not the aid per se, improves performance owing to psychological factors. Athletes and others must carefully examine claims made by the dietary supplements industry, including the scientific evidence that supports the claims. A solid understanding of research development and experimental procedure is important in judging the validity of an ergogenic aid.
- Sports bars provide energy as well as other essential nutrients. Their composition may vary based on the intended consumer and purpose of the sports food. Some sports bars are marketed as a quick and high-energy source, so that they can be used before or after intense training or sports competitions. Others are designed to be meal replacements that contain a high amount of protein and/or fiber.
- Carbohydrate is usually the energy foundation of many sports bars that are consumed before and after exercise. Many sports bars also contain fibers and protein, as well as vitamins and minerals directly involved in energy metabolism, such as B vitamins, magnesium, zinc, and iron.
- Sports drinks may be broken down into two categories: (1) fluid and electrolyte replacement drinks in which the carbohydrate content is relatively low; and (2) drinks that contain a higher carbohydrate formulation. The former is more appropriate for use during exercise, whereas the latter is suited better for consumption after training or in preparation for an upcoming event.
- In sports drinks, carbohydrate is typically provided as glucose, sucrose, fructose, corn syrup, maltodextrins, and glucose polymers. They also contain plenty of electrolytes, including sodium, potassium, and chloride. The carbohydrates usually make up about 4 to 8 percent of a fluid/electrolyte replacement drink and >10 percent of a recovery/loading beverage. A more diluted concentration will help facilitate gastric emptying, thereby enhancing fluid/electrolyte replacement.

- Intense resistance training may lead to muscle fatigue and soreness as well as muscle structural damage. As such, supplementing BCAA, whey, and/or casein will provide added amino acids needed for muscle recovery and adaptation. These protein-based supplements have their unique features so that their combined use may help reach the intended outcomes more effectively.
- Despite such a large quantity of ergogenic aids, the working mechanism of each may be explained by one or more of the following: (1) they act as a central or peripheral nervous system stimulant; (2) they increase storage or availability of a limiting substrate; (3) they act as a supplemental fuel source; (4) they reduce performance-inhibiting metabolic by-products; (5) they facilitate recovery; and (6) they enhance tissue synthesis.
- Arginine, ornithine, lysine, bicarbonate, boron, caffeine, hydroxy citric acid, carnitine, chromium, co-enzyme Q_{10}, creatine, DHEA and androstenedione, ephedrine, glutamine, glycerol, HMB, inosine, nitrate oxide, phosphate, and P-synephrine are the popular ergogenic choices. However, most remain inconclusive in terms of their efficacy and/or potential risks. The existence of such inconsistencies may in part be related to the differences in the experimental protocol, i.e., dosage and duration of supplementation, number and type of subjects, exercise mode and intensity, testing and measurement, and control of diet and physical activity.

Case study: making a sound decision on an ergogenic aid

Andy is a running back on the college football team. He also competes for the wrestling team. Andy is always very conscious about his diet. He eats a balanced diet and takes multivitamins and mineral supplements each day. He would like to improve his strength and power as well as his body composition, and decides to experiment with some ergogenic aids. Based on the articles and advertisements he has read in sports magazines, he selects creatine for improving his strength and power and HMB (*β*-Hydroxy-*β*-methylbutyrate) to improve his muscle mass and body composition. But before he begins taking these aids he wants to explore their risks and benefits as well as their working mechanism.

Questions

- What is the exact working mechanism by which creatine improves performance? What about HMB?
- Do these supplements live up to their promoter's promises?
- Where should Andy look if he needs more authentic information on these products?
- Would you recommend that Andy takes these supplements? Why?

Review questions

1 What is a double-blinded experiment? What are advantages associated with this research design?
2 Why is it necessary to use a placebo in research studies on ergogenic aids?
3 Provide one example of an ergogenic aid that fits each of the following claims: (1) it acts as a central or peripheral nervous system stimulant; (2) it increases storage or availability of a limiting substrate; (3) it acts as a supplemental fuel source; (4) it reduces performance-inhibiting metabolic by-products; (5) it facilitates recovery; and (6) it enhances tissue synthesis.

4 Explain how supplementing BCAAs may reduce serotonin production, thereby delaying mental fatigue.
5 What is the ergogenic property of bicarbonate loading? To what types of sports will this product be most applicable? Why?
6 Boron, chromium, and creatine are considered to produce a gain in muscle mass. How does each of them work physiologically in achieving this ergogenic effect?
7 List all ergogenic effects of creatine supplementation. What are the potential risks associated with this ergogenic aid? What types of athletes will benefit from supplementing creatine?
8 Explain how caffeine works in improving performance.
9 What are the claims associated with DHEA and androstenedione?
10 Ephedrine has been used to increase fat utilization. How does this effect come about? Why is caffeine often used in conjunction with ephedrine?
11 Explain why glycerol is used for enhancing hydration.
12 Discuss *β*-Hydroxy-*β*-methylbutyrate (HMB) in term of its origin and food sources. Why is this compound considered ergogenic?
13 How is phosphate related to enhancing performance?

Suggested reading

1 American College of Sports Medicine (1987) American College of Sports Medicine position stand on the use of anabolic-androgenic steroids in sports. *Medicine and Science in Sports and Exercise*, 19: 534–539.
This article allows readers to learn the position of the American College of Sports Medicine on the use of anabolic-androgenic steroids in sports.
2 American College of Sports Medicine (1987) American College of Sports Medicine position stand on blood doping as an ergogenic aid. *Medicine and Science in Sports and Exercise*, 19: 540–543.
This article allows readers to learn the position of the American College of Sports Medicine on the use of blood doping as an ergogenic aid for athletic competitions.
3 Armstrong LE (2002) Caffeine, body fluid–electrolyte balance, and exercise performance. *International Journal of Sport Nutrition and Exercise Metabolism*, 12: 189–206.
In this review, the author critiques several controlled investigations regarding the effects of caffeine on dehydration and athletic performance. It also analyzes the potential consequences of consuming caffeinated beverages on fluid–electrolyte balance and exercise capacity in both athletes and recreational enthusiasts.
4 Graham TE (2001) Caffeine, coffee and ephedrine: impact on exercise performance and metabolism. *Canadian Journal of Applied Physiology*, 26(Suppl): S103–S119.
This paper addresses areas where there is controversy regarding caffeine as an ergogenic aid and also identifies topics that have not been adequately addressed, such as using caffeine in conjunction with ephedrine.

Glossary

***β*-hydroxy-*β*-methylbutyrate** a metabolite of the essential amino acid leucine and used to prevent or reduce muscle damage and to suppress protein degradation associated with intense physical effort.

Androstenedione a steroid hormone that functions as a precursor between DHEA and testosterone.

ATP citrate lyase an enzyme that catalyzes reactions of fatty acid biosynthesis from carbohydrate.

Bicarbonate a salt of carbonic acid containing the ion HCO_3^{-2} that helps delay the onset of acidosis and thus fatigue.

Boron an essential trace mineral involved in bone mineral metabolism, steroid hormone metabolism, and membrane functions.

Branched-chain amino acids amino acids that have side chains with a branch (a carbon atom bound to more than two other carbon atoms), such as leucine, isoleucine, and valine.

Caffeine a naturally occurring substance found in a variety of beverages and foods, including coffee, tea, and chocolate.

Casein a part of milk proteins and derived from cheese making.

Chromium a trace mineral that potentiates insulin action and insulin stimulates the glucose and amino acid uptake by muscle cells.

Coenzyme Q_{10} referred to as ubiquinone that functions as an integral component of the mitochondrion's electron transport system.

Creatine a nitrogen-containing molecule used by the body to form high-energy compound phosphocreatine (PCr).

Dehydroepiandrosterone (DHEA) a steroid hormone that functions as a precursor to antrostenedione and testosterone.

Doping the use of drugs to enhance performance in sports.

Ephedrine a sympathomimetic amine commonly used as a stimulant, appetite suppressant, concentration aid, and decongestant.

Ergogenic increasing work or potential to do work.

Ergolytic having a negative effect on muscle capacity.

Glutamine a nonessential amino acid that assists in nitrogen transport between tissues, acid–base regulation, and production of antioxidant glutathione.

Glycerol a component of the triglyceride molecule and used for gluconeogenesis and water retention.

Hydroxy citric acid a derivative of citric acid found in a variety of tropical plants and marked as a weight loss supplement.

Inosine a purine ribonucleoside and used for ATP synthesis.

L-carnitine a substance that functions as a carrier protein to transport long-chain fatty acids into the mitochondrial matrix.

Nitric oxide a compound formed from L-arginine in the endothelial cells that line the blood-vessels and acting as a vasodilator to increase blood flow to muscles.

Phosphate loading ingesting phosphate and phosphorus prior to strenuous exercise for the purpose of enhancing ATP synthesis and oxygen delivery to muscle cells.

Sports supplements various nutritional and pharmacological ergogenic aids.

Synephrine an extract from the bitter or sour orange that functions as a stimulant.

Whey a part of milk proteins and derived from cheese making.

12 Nutrition and metabolism in special cases

Contents

Key terms

- Adolescence
- Childhood
- Estrogen
- Exogenous
- Gestational diabetes
- Glucose transporters
- Hyperinsulinemic glucose clamp
- Indirect calorimetry
- Insulin resistance
- Insulin sensitivity
- Lipoprotein lipase
- Metabolic inflexibility
- Oxygen kinetics
- Placental lactogen
- Progesterone
- Puberty
- Subcutaneous
- Thermogenesis
- Visceral
- Central obesity
- Corpus luteum
- Euglycemic
- Follicular
- Glucose tolerance
- Hemoglobin
- Hyperlipidemia
- Infancy
- Insulin responsiveness
- Leptin
- Luteal
- Oxygen deficit
- Placenta
- Post-absorptive state
- Prolactin
- Respiratory exchange ratio
- Testosterone
- Vastus lateralis

Gender differences in substrate metabolism

In the not-so-distant past, our society was influenced by the notion that boys were meant to be active and athletic, whereas girls were weaker and thus less well suited to physical activity. In fact, women were prohibited from running any race longer than 800 m until the 1960s (Wilmore and Costill 2004). This notion is no longer true, and girls and women are given equal access to most athletic activities. Due to increased involvement in physical activity and training, there has been a tremendous decrease in the gender gap in terms of athletic performance. In events other than those requiring muscular strength and power, performance differences between genders are no more than 15 percent. The current knowledge of metabolic responses to exercise and training is based largely on responses of young adult males. This is because much of the previous research in the area of exercise metabolism has been conducted using primarily male subjects. Due to the ever-increasing involvement of women in sports and leisure and occupational

physical activities, there has been a steady increase in research that aims to compare exercise-induced metabolic responses and adaptations between genders. Understanding such gender differences will help establish more appropriate gender-specific dietary and exercise guidelines.

Gender differences in energy expenditure

On average, women's total energy expenditure, which is the number of calories burned for metabolic needs, including breathing, blood circulation, digestion, and physical activity, is around 5 to 10 percent lower than men's. This reduced energy expenditure may be partly explained by body composition. Body composition (i.e., the amount of muscle, bone, and fat that make up the body) is quite different between men and women. Men, in general, have more muscle mass, heavier bones, and less body fat than women. For example, a typical adult man who weighs 154 pounds has 69 pounds of muscle, 23 pounds of bone, and 23 pounds of fat. A typical adult woman of the same age who weighs 125 pounds has 45 pounds of muscle, 15 pounds of bone, and 34 pounds of fat. The recommended percentage of body fat for a woman is between 20 to 30 percent which is thought to be higher for childbearing, while the recommended range for a man is between 10 and 20 percent. Because of these differences in muscle mass, men burn more calories than women at rest.

Physical activity differences appear to also play a role. Women, in general, tend to be less active than men. In a study that measured metabolism in both middle-aged men and women, Carpenter *et al.* (1998) found that total daily energy expenditure was 16 percent lower in women compared to men due to a 6 percent lower resting metabolic rate and a 37 percent lower physical activity energy expenditure. This finding suggests that the main reason why women's energy expenditure was lower was due to significantly fewer calories burned from physical activity. Of particular interest is that authors revealed these gender differences in energy expenditure after taking into account the differences in body composition.

Substrate utilization of males and females

Although there is some disagreement, perhaps the most repeatedly evidenced metabolic difference between genders is that, compared to men, women are able to derive proportionally more of the total energy expended from fat oxidation during aerobic exercise. This conclusion was drawn primarily from studies using **indirect calorimetry**, a method that calculates heat which living organisms produce from their consumption of oxygen. In these studies, a lower **respiratory exchange ratio** (RER) during submaximal endurance exercise was found in females as compared to males. As discussed in Chapter 11, RER is a qualitative indicator of which fuel (carbohydrate or fat) is being metabolized to supply the body with energy, and the lower the RER, the greater the percentage of energy derived from fat. In these studies, an effort was made to match male and female subjects for their VO_2max or training status. This approach was used to preclude the potential confounding effect of fitness on the gender-related difference in exercise metabolism. In these studies, oxygen uptake was also normalized relative to lean body mass in order to minimize the gender differences in energy metabolism that is attributable to percentage of fat.

The evidence with indirect calorimetry that women oxidize fewer carbohydrates and more fat during exercise is consistent with investigations that have involved more sophisticated laboratory techniques, i.e., muscle biopsy and isotopic tracer methods. For example, Tarnopolsky *et al.* (1990) found that **vastus lateralis** glycogen concentration

was less depleted in women following exercise. In this study, authors had six males and six equally trained females run for more than 90 minutes at 65 percent VO_2max following three days on a controlled diet. Muscle glycogen utilization was calculated from pre- and post-exercise needle biopsies of vastus lateralis. Using a different analytic approach, Carter *et al.* (2001b) also observed a lower utilization of muscle glycogen in women than in men during endurance exercise both before and after endurance training. In these studies, lipid oxidation as determined by indirect calorimetry was found to be uniformly higher in women than in men during exercise at the same relative intensity.

Underlying mechanism: the role of sex hormones

According to the currently available research, gender differences in exercise metabolism seem to be mediated primarily by sex hormones such as **estrogen** and **progesterone**, which present in small quantities in men as well. Progesterone, released from the **corpus luteum**, **placenta**, and adrenal glands, is considered a precursor to the male and female sex hormones, testosterone and estrogen, respectively. Estrogen is a collective term for a group of 18-carbon steroid hormones. The most biologically active estrogen is 17β-estradiol (E_2), and there are other less potent estrogens such as estrone (E_1) and estriol (E_3). Estrogens are secreted mainly by the ovaries and, to a lesser extent, by the adrenal glands. Estrogens are also synthesized from androgens such as **testosterone** in blood or other organs such as adipose and muscle tissues.

Animal studies of estrogen and progesterone

A number of animal studies have been undertaken to examine the impact of estrogen upon the utilization of glycogen. In these studies, the experimental approach is to alter the hormonal environment by injecting estrogen and then to evaluate the metabolic consequences. For example, Kendrick *et al.* (1987), who administered E_2 to rats in doses sufficient to achieve blood levels of estrogen in the physiological range, showed decreased utilization of glycogen stored in skeletal muscle as well as in the heart and liver. The role of progesterone in exercise metabolism is less clear. It has been reported that this hormone increases liver glycogen content and suppresses hepatic gluconeogenesis, and these effects can be enhanced by concurrent administration of E_2. In this context, it appears that the two female hormones may work additively or synergistically in reducing carbohydrate utilization during exercise.

High levels of E_2 have also been found to increase the availability of free fatty acids (FFA) during exercise in rats. For example, Ellis *et al.* (1994) observed that during exercise E_2 increased lipolysis in adipose tissue and enhanced the distribution of FFA to the muscles. This increased availability of FFA may be further attributed to the alterations in activity of **lipoprotein lipase** (LPL) that regulates fat metabolism. In this same study, Ellis *et al.* demonstrated a decreased activity of adipocyte LPL, which promotes fat synthesis, and an increased activity of muscle LPL, which promotes fat utilization. Of particular interest is that estrogen and progesterone would play an opposing role in regulating fat metabolism, which is not the case in terms of their actions on carbohydrate metabolism. Campbell and Febbraio (2001) observed an increased activity in several key enzymes involved in fatty acid oxidation as a result of estrogen supplementation, while such an effect was reversed with the concurrent administration of progesterone. The roles which estrogen and progesterone play in regulating fat and carbohydrate metabolism are illustrated in Table 12.1.

Table 12.1 The actions of estrogen and progesterone on carbohydrate and fat metabolism

Actions	*Estrogen*	*Progesterone*
Carbohydrate metabolism		
Muscle glycogenolysis	Inhibiting	Inhibiting
Liver glycogenolysis	Inhibiting	Inhibiting
Glucose transport into muscle	Inhibiting	Inhibiting
Fat metabolism		
Adipose tissue lipolysis	Stimulating	Inhibiting
Fatty acids transport into mitochondria	Stimulating	Inhibiting

Source: adapted from Deon and Braun (2002).

Observations with human subjects

The effect of sex hormones on energy metabolism has also been examined using humans. Hackney (1990) performed muscle biopsies on the vastus lateralis of ten healthy women in both the **follicular** and **luteal** phase of the menstrual cycle. They found that under resting conditions muscle glycogen content was higher in the luteal than in the follicular phase. Subsequently, this same research group also reported a lower carbohydrate oxidation in the luteal phase during exercise at 35 and 60 percent VO_2max (Hackney *et al.* 1994). Since the luteal phase is when production of both estrogen and progesterone was higher, this finding is consistent with the conclusion of animal studies that estrogen attenuates the utilization of carbohydrate. The inhibitive role of estrogen on carbohydrate utilization was also evidenced in studies in which subjects were supplemented with **exogenous** estrogen. By providing 17*ß*-estradiol or E_2 to a group of amenorrhoeic females, Ruby *et al.* (1997) observed altered carbohydrate metabolism. In this study, an isotopic tracer method was used so that investigators were able to determine muscle glucose utilization and hepatic glucose production. It was found that the release of glucose from the liver was reduced as a result of increased E_2 levels during exercise, while glucose utilization by muscle remained similar between E_2 and placebo groups. Such a reduction in hepatic glucose output due to E_2 supplementation was also observed by Carter *et al.* (2001a), who administered E_2 to a group of men, although this research group found a decrease in muscle glucose utilization. In both studies, no differences in whole body substrate oxidation were found between the experimental and placebo group. It appears that despite the indication from animal studies that estrogen may mitigate muscle glycogen utilization, such a role of estrogen in humans is less conclusive.

Muscle glycogen synthesis

Given the attenuation in glycogen utilization during exercise seen in women, it is likely that the ability for women to respond to glycogen supercompensation would reduce. Tarnopolsky *et al.* (1995) examined gender differences in the response of muscle glycogen to a modified carbohydrate loading protocol whereby exercise intensity was tapered for 4d and dietary carbohydrate intake was either 57 or 75 percent of total energy intake. As a result of the higher carbohydrate intake, the male subjects demonstrated a 41 percent increase in muscle glycogen and a 45 percent improvement in endurance performance, whereas the female subjects showed no increase in muscle glycogen and no effect on performance. The authors suggested that the failure of women to increase their glycogen content was due to insufficient carbohydrate intake. For example, in that

study, the energy intake was 4.8 and 6.4 g kg^{-1} d^{-1} for females and 6.6 and 8.2 kcal kg^{-1} d^{-1} for males, respectively, on the low and high carbohydrate diet. It has been recommended that an effective carbohydrate loading protocol must require an intake of carbohydrate at 8 to 10 kcal kg^{-1} d^{-1} (Burke and Hawley 1999). The findings of this study may also be explained by potential gender differences in muscle glycogen synthesis and/or glucose uptake, although this assertion remains to be validated.

Protein metabolism

In the basal state, men and women have virtually identical turnover rates of muscle protein when the rates are normalized to lean mass (Burd *et al.* 2009, Smith *et al.* 2009). During exercise, however, women seem to rely less on protein as a substrate during exercise than do their age-matched male counterparts. Early studies by Tarnopolsky *et al.* (1990) suggest that males oxidize proportionately more protein during exercise based on the observation that males increased 24-hour urinary urea nitrogen excretions following endurance exercise compared to a resting condition, whereas females did not. This same research group also found that males oxidize proportionately more leucine during exercises as compared to females (McKenzie *et al.* 2000). The ability to synthesize muscle protein is lower in women as compared to men, and this is especially the case in older women (Burd *et al.* 2009). In general, women would have a reduced capacity for hypertrophy in response to resistance training compared to men. Interestingly, a sexual dimorphism has been observed; that is, compared to men, women have reduced muscle protein synthesis, but lose muscle protein more slowly as they age (Smith *et al.* 2008).

Nutritional considerations

Women, like men, should enjoy a variety of foods, such as wholegrains, fruits, vegetables, healthy fats, low-fat dairy and lean protein. But women also have special nutrient needs, and, during each stage of a woman's life, these needs change. Iron is one of the keys to good health and energy levels in women. Women of reproductive age are at risk for iron deficiency anemia because of iron loss due to menstruation. Iron-rich food sources include red meat, chicken, turkey, pork, fish, kale, spinach, beans, lentils, and fortified breads and cereals. Plant-based sources of iron are more easily absorbed by the body when eaten with vitamin C-rich foods, so consider eating fortified cereal with strawberries on top, spinach salad with mandarin orange slices, or add tomatoes to lentil soup. **Hemoglobin**, the oxygen-carrying protein in red blood cells, binds oxygen via iron. Thus, iron deficiency may result in a reduced oxygen delivery to tissues. Female athletes, especially those who participate in endurance sports such as distance running, must include iron-rich foods in their diet or risk incurring iron-deficiency anemia and impaired running performance.

Another nutrient of concern for women is calcium owing to an increased risk of osteoporosis in women. Osteoporosis occurs in both men and women, but 80 percent of those affected by osteoporosis are women. Osteoporosis-related fractures occur in one out of every two women over the age of 50 compared to about one in every eight men of the same age (Osteoporosis Prevention, Diagnosis, and Therapy, 2000). The greater risk of osteoporosis in women is because men have a higher peak bone mass to begin with and because bone loss is accelerated in women for about five years after menopause due to a drastic decline in estrogen levels. Being smaller in size, women need fewer calories than men, yet many may not consume adequate energy and may develop disordered eating habits as they attempt to lose body mass for competition purposes. Disordered

eating is more prevalent in female athletes and may contribute to the development of premature osteoporosis. Consequently, for healthy bones and teeth, women, including athletes, need to eat a variety of calcium-rich foods every day. Some calcium-rich foods include low-fat or fat-free milk, yogurt and cheese, sardines, tofu (if made with calcium sulfate), and calcium-fortified foods including juices and cereals. Table 12.2 provides a list of more specific dietary recommendations which women should consider in order to maintain health, fitness, and optimal performance.

Pregnancy

Pregnancy places unique demands on women's metabolism. When women become pregnant, mechanical changes related to weight gain (increases in breasts, uterus, and fetus) result in a reallocation in a woman's center of gravity. This weight shift affects the metabolic cost and physiological strain imposed by exercise. An earlier investigation studied 13 women from six months of pregnancy to six weeks after gestation (Knuttgen and Emerson 1974). It was found that during walking, HR and VO_2 increased progressively despite no change in exercise intensity. However, these two parameters remained constant throughout steady-state cycle exercise. These findings suggest that due to an increase in body mass including fetal tissue, there would be an increase in energy cost during weight-bearing activities like walking, jogging, and running. In addition to this added energy cost during exercise, it has also been demonstrated that pregnant women will have an increase in resting metabolism especially during the later stages of pregnancy. Table 12.3 provides a comparison in caloric cost of common household activities between pregnant and non-pregnant women. It has been estimated that throughout the entire pregnancy, there would be an addition of 75,000 kcal required to build new tissues and to meet the demands of higher energy costs of daily activities. This figure represents an extra expenditure of 250 kcal per day during a 10-month pregnancy period. Despite increased energy costs of weight-bearing activities, it has been assumed that such an increase in energy cost is offset by a decrease in the amount of time spent in weight-bearing activities as well as by the relaxed and economical fashion in which pregnant women move. Consequently, the net increase in energy expenditure associated with pregnancy may only reflect an increase in resting metabolism as a result of growing of both maternal and fetal tissues.

Table 12.2 Food choices important for women's health

Foods to recommend	• At least three 1-ounce servings of wholegrains such as wholegrain bread, cereal, pasta, brown rice, or oats. • Three servings of low-fat or fat-free dairy products, including low-fat or fat-free milk, yogurt, or cheese. • Five to 6 ounces of protein such as lean meat, chicken, turkey, fish, eggs, beans or peas, and nuts. • Two cups of fruits – fresh, frozen, or canned without added sugar. • Two-and-a-half cups of colorful vegetables – fresh, frozen, or canned without added salt.
Foods to limit	• Limit regular soft drinks, sugar-sweetened beverages, candy, baked goods and fried foods. • Limit alcohol intake to one drink per day (*i.e., 12 ounces of beer, 5 ounces of wine, or 1.5 ounces of liquor*). • Limit foods that are high in saturated fat (*i.e., those found in fatty meats, sausages, cheese and full-fat dairy products, baked goods and pizza*).

Table 12.3 Comparisons of energy cost of household activities in pregnant and non-pregnant women

Activity	*Energy cost (kcal·min^{-1})*	
	Pregnant	*Non-pregnant*
Lying quietly	1.11	0.95
Sitting	1.32	1.02
Sitting, combing hair	1.36	1.22
Sitting, knitting	1.55	1.47
Standing	1.41	1.12
Standing, washing dishes	1.63	1.33
Standing, cooking	1.66	1.41
Sweeping with broom	2.90	2.50
Bed-making	2.98	2.66

Sources: Brooks *et al.* (2005). Used with permission.

Substrate metabolism during pregnancy

Although pregnancy consists of a series of small, continuous physiological adjustments, the alterations in substrate metabolism appear to occur primarily during the later phase of pregnancy. From a metabolic standpoint, pregnancy may be divided into phases such as the first and second halves. The first half of pregnancy is primarily a time of preparation for the demands of rapid fetal growth that occurs later in pregnancy. During this period, there is a continuous increase in the production of estrogen and progesterone. The presence of these hormones can help not only mobilize fat for energy but also stabilize plasma glucose at relatively high levels in order to meet the needs of the fetus. There is evidence that perhaps as a means of protecting the fetus from hypoglycemia, pregnancy reduces the ability of the mother to metabolize carbohydrate (Clapp *et al.* 1987). This metabolic alteration could inhibit pregnant women from performing anaerobic or strenuous aerobic exercises in which carbohydrate is a primary fuel.

For pregnant women, measurement of insulin sensitivity is often used to detect the possibility of **gestational diabetes**. This is because estrogen and **placenta lactogen** have been considered diabetogenic hormones due to their inhibitive effects on insulin-mediated glucose uptake by various tissues. A number of studies have reported that during the early phase of pregnancy, the sensitivity of peripheral tissues to insulin was either normal or slightly increased (Buch *et al.* 1986, Gatalano *et al.* 1991). However, longitudinal studies of glucose tolerance have shown that as gestation continues, there would be a progressive increase in insulin response to a given dose of glucose challenge (Sivan *et al.* 1997). This greater-than-normal insulin response is consistent with the phenomenon of **insulin resistance** and suggests that pregnant women can potentially diminish their ability to handle glucose with insulin. This deficiency is especially the case in obese pregnant women who have a high risk of developing diabetes even without pregnancy (Sivan *et al.* 1997). The reduced insulin sensitivity is thought to be secondary to the gestation-induced changes in hormones including estrogen, progesterone, cortisol, **prolactin**, etc., although the precise mechanism remains unclear. From a fetal standpoint, a certain degree of insulin resistance is considered desirable in that it can serve to shunt ingested nutrients to the fetus.

Exercise during pregnancy

During pregnancy, the metabolic reserve available for performing exercise is diminished owing to increased resting metabolism and blunted sympathetic response to physical activity. However, during the early stages of pregnancy, light to moderate activity can be pursued safely, given that blood glucose is carefully monitored to prevent hypoglycemia. Regular exercise during pregnancy counteracts the effects of deconditioning. It attenuates pregnancy-related fatigue. It helps maintain muscular strength, which may speed delivery. It can also prevent excessive weight gain, insulin resistance, and type 2 diabetes. Based on the previous literature, it appears that ordinary pregnant women are able to tolerate light- to moderate-intensity exercise sessions of up to 30 minutes in duration and four times per week, although exercise tolerance may be affected by environmental conditions as well as the fitness level of the mother. A concern based on animal studies has been raised that maternal exercise may increase fetal temperature, which can contribute to congenital abnormalities, but no such evidence has been shown in humans (Wang and Apgar 1998). Caution should be taken in selecting appropriate exercise modality. With the advancement of pregnancy, the capacity for exercise, especially those activities that occur against gravity, decreases. Therefore, during the later stages of pregnancy, it is helpful to introduce weight-supported activities such as cycling, swimming, and water aerobics. Exercise can be dangerous if excessive. Important contraindications to vigorous exercise include hypoglycemia, intrauterine growth retardation, premature labor and/or ruptured membrane, placental injury or dysfunction, an incompetent cervix, pregnancy-induced hypertension, and blood poisoning (Artal and O'Toole 2003).

Nutritional considerations

Pregnancy is a time of increased energy and nutrient needs. Energy needs during pregnancy increase 150 kcal per day during the first trimester and then rise to 300 to 350 kcal per day during the second and third trimesters. If a woman also exercises, her energy needs will increase above those required for pregnancy. As discussed in earlier chapters, the increase in energy needed for exercise will depend on the type, intensity, frequency, and duration of the activity. Benefits of exercise include lower wright gain, an easier and less complicated labor, more rapid recovery after labor, and improved overall fitness.

The RDAs for protein and carbohydrate are increased during pregnancy. The additional protein is needed because protein is essential for the formation and growth of new cells. During pregnancy, the placenta develops and grows, the uterus and breast enlarges, and a single cell develops into a fully formed infant. An additional 25 grams of protein per day above RDA for non-pregnant women or 1.1 g kg^{-1} is recommended for second and third trimesters of pregnancy. For a woman weighing 132 lb (60 kg), her protein requirement is about 70 grams per day. This is the amount of protein in 3 cups of milk or yogurt plus 5 to 6 oz of meat. It is recommended that a pregnant woman raises her carbohydrate intake by 45 to 50 grams per day in order to provide sufficient glucose to fuel the fetal and maternal brains. However, adding this amount to the existing RDA for carbohydrate totals up to 175 grams per day. This is well below the typical intake of about 300 grams per day, and therefore most women don't need to consciously increase their carbohydrate intake.

The need for many vitamins and minerals is increased during pregnancy. Due to the growth in maternal and fetal tissues as well as increased energy utilization, the requirements for B vitamins, such as thiamin, niacin, and riboflavin, increase. To form new maternal and fetal cells and to meet the needs for protein synthesis, the requirements for folate, vitamin B12, vitamin B6, zinc, and iron increase. The needs for calcium,

Table 12.4 Daily food checklist recommended for pregnancy

Food group	*1st trimester*	*2nd and 3rd trimesters*	*What counts as 1 cup or 1 ounce?*
Fruits	2 cups	2 cups	• 1 cup fruit or 100% juice • 1/2 cup dried fruit
Vegetables	2 1/2 cups	3 cups	• 1 cup raw or cooked vegetables or 100% juice • 2 cups raw leafy vegetables
Grains	6 ounces	8 ounces	• 1 slice bread • 1 ounce ready-to-eat cereal • 1/2 cup cooked pasta, rice, or cereal
Protein	5 1/2 ounces	6 1/2 ounces	• 1 ounce lean meat, poultry, or seafood • 1/4 cup cooked beans • 1/2 ounce nuts or 1 tbsp peanut butter • 1 egg
Dairy	3 cups	3 cups	• 1 cup milk • 8 ounces yogurt • 1 1/2 ounces natural cheese • 2 ounces processed cheese

Note
If you are not gaining weight or gaining too slowly, you may need to eat a little more from each food group. If you are gaining weight too fast, you may need to cut back by decreasing the amount or change the types of foods you are eating.

vitamin D, and vitamin C increase to provide for the growth and development of bone and connective tissue. Table 12.4 illustrates the daily food checklist that allows for a proper intake of the major nutrients important at various stages of pregnancy.

Supplementations, especially for iron and folic acid, are typically provided by the physician during pregnancy. A woman's folic acid needs double during pregnancy. This is to also prevent neural tube defects (in which the child is born with an underdeveloped brain) or spina bifida (in which the spinal cord does not completely close). Foods that naturally contain folate include citrus fruits, leafy greens, beans, and peas, and there are many folic acid-fortified foods such as cereals, rice, and breads. Iron needs of a pregnant woman also increase especially in the later stages of pregnancy in order to allow for the synthesis of hemoglobin and other iron-containing proteins in both maternal and fetal tissues. Even though iron losses are decreased due to the cessation of menstruation, iron-deficiency anemia is common during pregnancy. This is in part because low iron stores are common among women of childbearing age, so many women start pregnancy with diminished iron stores and quickly become deficient.

The elderly

The elderly (i.e., those who reach and pass the age of 65) make up the fastest-growing segment of our society today. For example, currently in the US approximately 35 million or nearly 12 percent of Americans exceed the age of 65. It is predicted that this figure will climb to 70 million or 22 percent of the population by 2030. Such a trend seen in the US should also apply in many Western nations and may soon emerge in developing countries. Aging refers to the normal yet irreversible biological changes that occur throughout an individual's life span. It involves a diminished capacity to regulate the internal environment in order to meet external challenges. As shown in Table 12.5, such

Table 12.5 Aging-related metabolic changes and their physiological consequences

Metabolic change	*Physiological consequences*
Myosin-ATPase ↓	Reduced muscle contractility
Lactate dehydrogenase ↓	Reduced glycolysis
Succinic dehydrogenase ↓	Reduced oxidative capacity
Malic dehydrogenase ↓	Reduced oxidative capacity
Cytochrome oxidase ↓	Reduced oxidative capacity
Mitochondria size and number ↓	Reduced oxidative capacity
Type II muscle fibers ↓	Reduced muscle strength and power
Capillary density ↓	Reduced oxygen delivery
Glucose tolerance ↓	Increased risk of diabetes and heart diseases
Blood insulin ↑	Increased risk of diabetes and heart disease
Insulin sensitivity ↓	Increased risk of diabetes and heart disease
Sympathetic stimulation ↓	Reduced maximal heart rate and lipolysis
Muscle mass ↓	Reduced basal metabolism and fat oxidation

a reduced ability may be further attributed to a series of attenuated or impaired physiological and metabolic functions, which ultimately reduce one's ability to generate the energy needed. Aging is influenced by genetics. This may be attested by observations that the life span of twins is remarkably similar. Identical twins usually die within two to four years of each other, whereas non-identical twins die within seven to nine years of each other. Aging is also affected by lifestyle factors. It is considered the process associated with an accumulation of wear-and-tear that leads to gradual loss of the ability to respond to stress. On the other hand, although it may not halt the aging process, regular physical activity and a healthy diet can help improve quality of life and prolong life expectancy.

Changes in body composition

Aging causes various changes in body composition, which have important consequences for health and physical functions. There is a progressive decrease in lean body mass and an increase in body fat. Decreased physical activity accounts for the increase in body fat, and this may lead to decreased energy intake with aging. These changes in body composition, including those in fat distribution, may be associated with changes in various physiological functions that affect metabolism, nutrient intake, physical activity, and risk for chronic diseases. Sarcopenia is another age-related change. The loss of lean muscle mass may lead to a gain in body fat. It may be more noticeable through loss of strength, functional decline, and poor endurance with aging. This loss also leads to reduced total body water content. There is also an alteration in bone density that results from a decrease in mineral content which occurs with aging. Loss of bone density may in turn increase the risk for osteoporosis. Severe osteoporosis may cause the bones in the legs to bow under the weight of the body. This bowing, together with changes in the spine, makes measurement of height unreliable in some elderly people, even in those who are able to stand unaided.

Reduced gastrointestinal functions

Effects of aging on the perceptions of smell and taste have been observed, which may alter or decrease food intake. This is a common perceived problem among elderly

individuals who complain of a loss of both taste and smell. Impaired appetite is often associated with a reduction in taste and smell, which occurs in up to 50 percent of elderly people. Diminished senses of taste and smell make food less appealing. These changes typically alter eating habits and reduce nutrient availability and absorption, which may lead to nutritional deficiencies. Various other changes occur throughout the digestive system. There is a decrease in gastric acid secretion, which may limit the absorption of iron and vitamin B12. Saliva production decreases, leading to slower peristalsis and constipation. Other gastrointestinal changes occur with age and may affect food intake. For example, greater satiation after a meal and a delay in gastric emptying have been observed in older people.

Reduced aerobic capacity and energy expenditure

Reductions in physical capacity may be characterized by a decrease in aerobic power or VO_2max, which was observed more than half a century ago. With cross-sectional comparisons, Robinson (1938) demonstrated that in men VO_2max declines at an average of 0.44 ml kg^{-1} min^{-1} per year up to age 75. This is translated into about 1 percent per year or 10 percent per decade. For women between the ages of 25 and 65, Åstrand (1960) showed a decline of 0.38 ml kg^{-1} min^{-1}, or 0.9 percent per year. Since these early observations there have been numerous cross-sectional and, to a lesser extent, longitudinal studies attempting to further characterize such age-related decline in VO_2max and its metabolic consequences. The rate of decline in VO_2max found in these studies in general agrees to what was reported initially by Robinson in 1938. A reduction in VO_2max due to aging has been further ascribed to a decrease in maximal heart rate, maximal cardiac output, and maximal ability of working muscle to utilize oxygen for energy transference.

Goran and Poehlman (1992) observed a significant correlation between VO_2max and total daily energy expenditure. In this study, authors also found a modest relationship between the total daily energy expenditure and the level of physical activity. These findings suggest that those with a greater aerobic fitness tend to be more physically active and therefore have greater daily energy expenditure. However, such a linkage between fitness level and energy expenditure provides no information of cause and effect. In other words, it is unclear whether the increased total energy expenditure associated with a physically active lifestyle leads to a higher VO_2max, or alternatively, whether those individuals with a higher VO_2max engage in physical activities more frequently and intensely because of the higher work capacity.

A reduction in total energy expenditure has been well evidenced in the elderly (Margaret-Mary and Morley 2003, Elia *et al.* 2000). Interestingly, many normal-weight healthy older men and women decrease their energy intake well below their energy expenditure and thus lose weight. In addition to lack of physical activity, the age-related decrease in energy expenditure has also been linked to reductions in basal metabolic rate and diet-induced **thermogenesis**. More detailed discussion on these two energy components may be found in Chapter 15.

Changes in enzymes of bioenergetic pathways

As mentioned earlier, mitochondria serves to allow biologically usable energy to be generated via oxidative pathways. Therefore, the frequently examined markers of mitochondrial function in skeletal muscle have been activities of selected oxidative enzymes and rate of ATP production. Numerous studies have all reported age-related decline in enzymes, such as citrate synthase, succinate-dehydrogenase, and cytochrome

c oxidase. Furthermore, with data provided by Holloszy *et al.* (1991), it appears that such reduction in activity of oxidative enzymes occurs primarily in red predominantly oxidative muscle than in white glycolytic muscles. As a result of these enzymatic changes, mitochondrial oxidative capacity is impaired. With the use of muscle samples, Papa (1996) observed a decreased ability of mitochondria to consume oxygen for generating energy. This *in vitro* observation is later confirmed by an *in vivo* study in which Conley *et al.* (2000) used nuclear magnetic resonance techniques and found that the average rate of ATP formation in the quadricep muscles of older subjects between the ages of 65 and 80 was approximately half that of subjects between the ages of 25 to 48.

Alterations in carbohydrate and fat metabolism

Another metabolic hallmark of the aging process is the impairment of carbohydrate and fat metabolism. Substantial evidence has been provided showing that increasing age is associated with decreased **glucose tolerance**. The glucose tolerance test measures the body's ability to metabolize glucose. It is performed after an overnight fast. During the test, a patient drinks a solution containing a known amount of glucose. Blood is obtained before the patient drinks the glucose solution, and is drawn again every 30 to 60 minutes after the glucose is consumed for two or three hours. Blood glucose levels above normal limits at the times measured may be used to diagnose type 2 diabetes or gestational diabetes. It has been estimated that the two-hour plasma glucose level during an oral glucose tolerance test rises on average 5.3 mg dl^{-1} per decade and the fasting plasma glucose rises on average 1 mg dl^{-1} per decade (Davidson 1979). Insulin, a hormone produced by the pancreas that moves glucose from the bloodstream into cells, has also been found to be higher in many older individuals. This observation suggests that the as one ages one may lose the ability to respond to insulin effectively and therefore require extra insulin to maintain normal blood glucose level.

The impairment in fat metabolism is another age-related metabolic disorder. Aging has been associated with reduced fat oxidation at rest (Nagy *et al.* 1996) and following a meal (Roberts *et al.* 1996). Sial *et al.* (1998) also demonstrated age-related reduction in fat oxidation during aerobic exercise. It is thought that these reductions in fat utilization play an important role in mediating the age-related increase in adiposity especially in the abdominal compartment. In the study by Sial *et al.* (1998), the authors also reported a greater carbohydrate oxidation, a finding that was thought to result from impaired fat utilization. All these age-related metabolic changes will gradually deprive the elderly of the ability to use their energy fuel efficiently during exercise as compared to younger individuals.

Fat oxidation is mainly a function of two processes, namely the release of fatty acids from adipose tissue and the capacity of respiring tissue to oxidize fatty acids. Previous studies using aging rats and humans have demonstrated a diminished sympathetic stimulation of lipolysis (Lönnqvist *et al.* 1990). However, when examined in relation to the needs of the metabolically active tissue, the release of free fatty acids was found to be greater in older compared to younger individuals (Toth *et al.* 1996). The age-related reduction in fat utilization is therefore considered to be primarily due to the loss of the size and/or oxidative capacity of metabolically active tissues such as skeletal muscle. Those fatty acids that are released but not metabolized could have adverse metabolic effects, such as **hyperlipidemia** and insulin resistance. In this regard, regular physical activity becomes particularly important because it can maintain or increase the size and function of skeletal muscle, thereby improving the health status of elderly individuals.

Nutritional considerations

Adults' energy needs typically decline with age. This is due to a decrease in all components of total energy expenditure that include basal metabolic rate (BMR), thermal effect of foods, and physical activity. These decreases are reflected in the energy needs of older adults. For example, the estimated energy requirement (EER) for an 80-year-old man is almost 600 kcal per day less than that for a 20-year-old man of the same height, weight, and physical activity level. Physical inactivity decreases energy needs even further. In fact, decreased physical activity is estimated to account for about half of the decrease in total energy expenditure that occurs with aging (Villareal *et al.* 2005). The decrease in activity also contributes to the reduction in lean body mass and BMR. As more research emerges, it is apparent that the best diet for older adults is one that is balanced with wholegrains, plenty of fruits, lean proteins, and plant proteins. By consuming a wide variety of nutrient-dense foods and engaging in physical activity, older adults can slow the loss in lean body mass that occurs naturally with aging. Besides observing the general recommendation to consume a balanced diet as discussed in Chapter 10, older adults may also refer to the food guide pyramid created by Tufts University which emphasizes specific nutrients of concern to older adults (Figure 12.1).

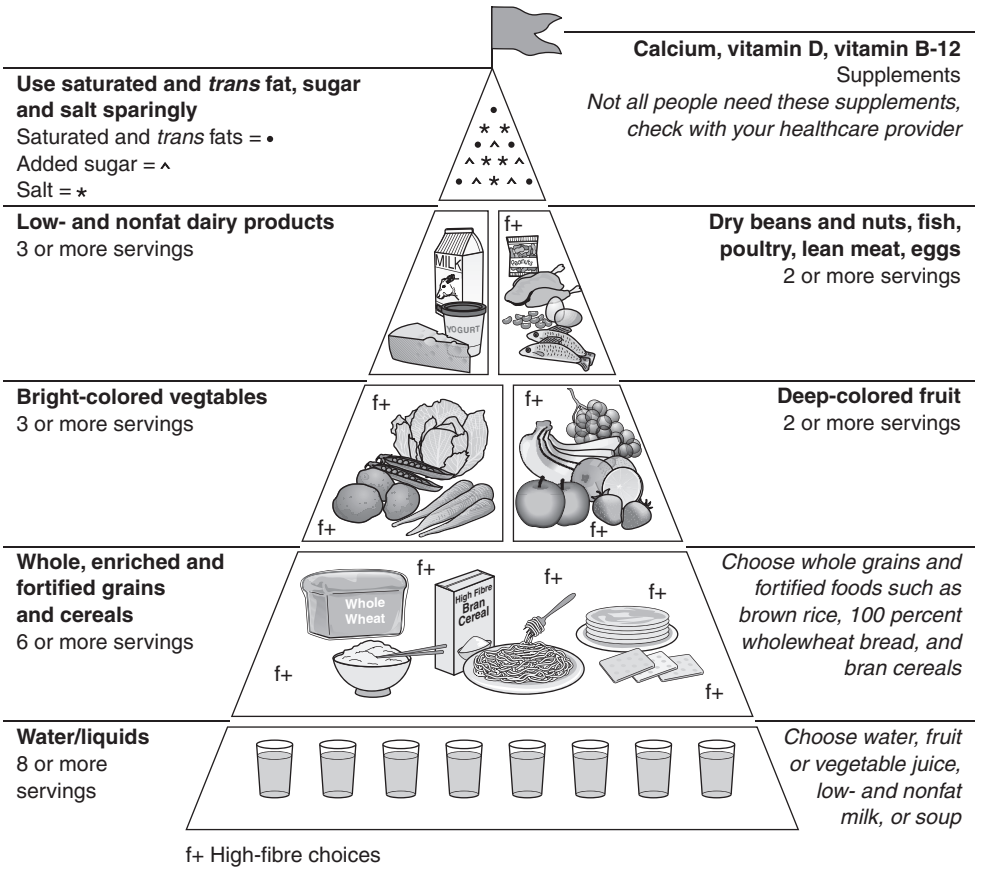


Figure 12.1 Food guides pyramid for older adults

Protein is needed at all ages to repair and maintain body tissues. Therefore, unlike energy requirements, the requirement for protein does not decline with age. However, the older adult who has drastically decreased his or her energy intake will often reduce protein intake as well, increasing the risk of protein malnutrition. RDA for adults is 0.8 g of protein per kg of body weight per day. However, this recommended amount is now considered inadequate for older adults due to reduced efficiency in protein utilization. Due to anabolic resistance that develops as one ages, the amount of protein required to stimulate protein synthesis would be greater in older adults as compared to their younger counterparts. Recent reports suggest that older adults consume 1.0 to 1.2 g/kg BW/day to maintain proper nitrogen balance and optimal health (Bauer *et al.* 2013).

The recommended proportion of energy from carbohydrate does not change with age, but the total amount needed may be lower in older adults due to lower energy needs. For example, as shown in the food guide pyramid created by Tufts University, the recommended servings for grain products are only 6 as compared to 6 to 11 designed for younger adults. The lower amount of carbohydrate recommended is also because reduced glucose tolerance is common among older adults, especially those who are inactive. Dietary carbohydrate should come from wholegrain, fruits, vegetables, and dairy products, and foods high in added sugars should be limited. This pattern will help assure adequate nutrients without excess energy.

Although the recommended intake for many micronutrients is no different for older adults than for younger adults, the decrease in energy intake that occurs with age causes a decline in the intake of many micronutrients, especially the vitamin Bs, vitamin D, calcium, iron, and zinc (American Dietetic Association 2005). These deficiencies if persistent could lead to a number of health concerns, such as impaired immune function, impaired wound healing, muscle weakness, and fatigue. To remedy these deficiencies, it has been suggested that older adults consider taking one multivitamin daily because this dose of supplementation is safe and inexpensive, and has been proved beneficial in preventing cardiovascular diseases, cancer, and osteoporosis (Fletcher and Fairfield 2002).

Children and adolescents

The period of life from birth to the start of adulthood may be divided into three phases: **infancy**, **childhood**, and **adolescence**. Infancy is defined as the first year of life. Childhood spans from the first birthday to the beginning of adolescence. The period of adolescence is more difficult to determine, but is often considered to begin at the onset of **puberty** and to terminate as growth and development are completed. Research on metabolism with regard to this early stage of life spectrum is relatively limited. This is mainly due to ethical considerations and methodological constraints in studying children and adolescents. For example, there are very few investigators who would puncture a child's artery or take a needle biopsy of a child's muscle. In addition, there is still an ongoing effort to search for instruments and protocols that are age- and/or size-appropriate. Consequently, our understanding of children's metabolic response to exercise has been based on a limited number of investigations. Many conclusions regarding exercise metabolism in children and adolescents are derived primarily from measurement of cardio-respiratory parameters such as oxygen uptake and respiratory exchange ratio.

Children and adolescents should not be regarded as miniature adults. In other words, the age-related functional deficiency in children and adolescents is not always attributable to the fact that they are smaller in size. It is generally true that children are less capable of performing a given task as compared to adults, yet their physiological function increases as they grow older and bigger. However, only some gains in physiological

function are proportional to changes in size. For example, muscle strength increases in direct proportion to its cross-sectional area. Many changes in function have been found to be either partially related to or completely independent of changes in size. For example, anaerobic capacity depends on the activity of some key anaerobic enzymes in addition to muscle size. It has also been found that some physiological parameters such as blood concentration of oxygen and glucose remain unchanged despite a gain in body size. It is important to understand the patterns of function–size relationship in growing individuals. This will help in making not only proper interpretations of age-related physiological differences, but also nutritional recommendations specific to children and adolescents.

Aerobic and anaerobic capacity

As mentioned earlier, VO_2max reflects the highest metabolic rate made available by aerobic energy transferring and this parameter may be expressed in both $l min^{-1}$ and $ml \cdot kg^{-1} min^{-1}$. As shown in Table 12.6, which depicts the chronological changes in VO_2max in $l \cdot min^{-1}$ reported by previous studies involving boys (n = 2180) and girls (n = 1730), VO_2max increases continuously until the age of 16 to 18 in boys, but increases minimally beyond the age of 14 to 15 in girls. Such gender difference in VO_2max may be ascribed in part to the differences in muscle mass between boys and girls (Davies *et al.* 1972). As a result of ratio scaling in which VO_2max in $l \cdot min^{-1}$ is divided by body mass, however, the average VO_2max in $ml\ kg^{-1}\ min^{-1}$ was still relatively higher in boys than in girls, especially during later periods of adolescence (Table 12.6). This finding suggests that the increase in VO_2max may also be explained by other factors such as those involved in oxygen transport and utilization that are gender specific. Over the years VO_2max in $ml\ kg^{-1}\ min^{-1}$ remains essentially unchanged in boys and slightly declines among girls. Thus, when comparing aerobic capacity using VO_2max already adjusted for body mass, one should expect no differences between children and adults. The decline in this relative VO_2max seen in girls may be due to a progressive increase in body fat in girls during adolescence.

Despite the fact that children often perform activities in an intermittent fashion, their anaerobic capacity is lower than that of adults. This lower anaerobic capacity may be manifested particularly in those short-term events that last for one to two minutes, such as a 400- to 800-m run or a 100- to 200-m swim. This is because children are less able to store glycogen as well as to extract energy from glycogen via glycolysis (Eriksson *et al.* 1971, 1973). The reduced anaerobic capacity in children may also be explained by a decreased sympathetic activity, which functions to simulate glycogenolysis and glycolysis. Pullinen *et al.* (1998) showed that adolescent males aged 15 ± 1 years have lower levels of blood catecholamines during resistance exercise as compared to adult males aged 25 ± 6 years. Interestingly, unlike glycogen, both storage and utilization of ATP and CP were

Table 12.6 Average maximal aerobic power in children and adolescents

VO_2max		*Age (years)*					
		6	*8*	*10*	*12*	*14*	*16*
VO_2max in $l \cdot min^{-1}$	Boys	1.0	1.3	1.6	2.1	2.7	3.5
	Girls	0.9	1.2	1.4	1.6	1.8	2.0
VO_2max in $ml \cdot kg^{-1} \cdot min^{-1}$	Boys	47	50	51	51	51	51
	Girls	46	46	45	43	42	40

Source: Adapted from Bar-Or and Rowland (2004).

found to be comparatively similar among children and adults (Zanconato *et al.* 1993, Eriksson *et al.* 1971). In these adult–children comparisons, the level of energy substrates was expressed relative to muscle mass to account for differences in body size.

Oxygen deficit and respiratory exchange ratio

Among other gas exchange parameters that have received a great deal of attention for children are oxygen kinetics and respiratory exchange ratios. **Oxygen kinetics** assesses the integrated responses of oxygen requirements and supply at the onset of and during exercise of varying intensity. VO_2 kinetics at the onset of exercise may be characterized by a phenomenon of **oxygen deficit**, which is defined as a lag of oxygen supply in relation to oxygen demand. A number of studies have attempted to examine VO_2 kinetics at the onset of aerobic exercise in children (Armon *et al.* 1991, Heberstreit *et al.* 1998, Sady 1981). In general, these studies agreed on the observation that children demonstrated a faster increase in oxygen uptake at the onset of exercise than did adults. It appears that children have the ability to activate their oxidative metabolism faster to meet the energy demands imposed by exercise. Aside from having a more prompted activation of the aerobic system, children are also found to be able to derive proportionally more of their total energy from fat oxidation. A number of studies have reported a lower RER in children than in adults (Martinez and Haymes 1992, Rowland *et al.* 1987), although this contention needs to be further evaluated as other studies have failed to observe this age-related difference (Rowland and Rimmy 1995, Macek *et al.* 1976).

Metabolic efficiency

When performing aerobic exercise, children are found to be less efficient than adults. This is manifested by a greater mass-specific oxygen uptake or VO_2 expressed in ml kg^{-1} min^{-1} observed in children. This metabolic feature is particularly the case during weight-bearing activities such as walking and running (Fawkner and Armstrong 2003). Sallis *et al.* (1991) have attempted to quantify the excessive metabolic cost of walking and running by compiling data from various studies. As shown in Figure 12.2, on average, a 5-year-old child would expend about 35 to 40 percent more oxygen than adults who perform the same task. This excess, however, decreases with age. It is suggested that the low economy of locomotion in children is caused by multiple reasons, including high resting metabolic rate, high stride frequency, mechanically wasteful locomotion style, and excessive co-contraction of antagonist muscles (Bar-Or and Rowland 2004).

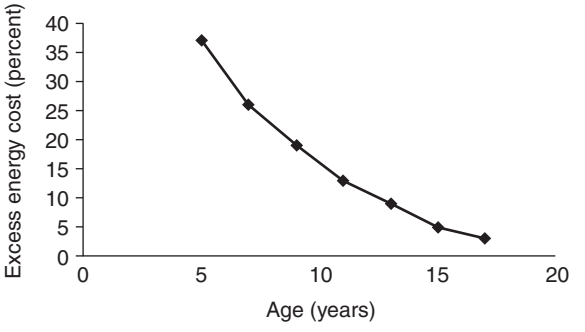


Figure 12.2 Excess oxygen cost of walking and running per kilogram body mass in children of various ages compared with young adults

Carbohydrate storage and utilization

Based on very limited data of muscle biopsies performed on children (Eriksson *et al.* 1973), it appears that there is a lower glycogen content at rest and reduced rate of glycogenolysis during exercise in children as compared to adults. Lundberg *et al.* (1979) also found that glycogen concentration in vastus lateralis in children investigated during surgery was lower than those observed in adults. The reasons for the low muscle glycogen content are not clear. However, muscle glycogen synthesis depends on glycogen synthase activity, which is mainly stimulated by insulin but also by insulin growth factor-1 (IGF-1). In this context, hormonal changes occurring during the pubertal period could contribute to the differences observed between prepubertal and adult subjects.

Children also demonstrate a reduced ability to use carbohydrate as an energy source. Early research has reported a lower RER in children than in adults (Martinez and Haymes 1992, Rowland *et al.* 1987), which is indicative of a greater percentage of energy derived from fat oxidation. The reduced use of carbohydrate may also be attributed to the lower muscle glycogen storage found in children (Eriksson *et al.* 1973, Lundberg *et al.* 1979). Glycogen utilization is regulated by the activity of such enzymes as phosphofructokinase and this enzyme has been found to be less active in muscle cells of boys as compared to adults (Eriksson *et al.* 1971, 1973, Bell *et al.* 1980). Taken altogether, it appears that there is a disadvantage for children to compete in prolonged strenuous events that are glycogen dependent. Endurance capacity may not be limited by the volume of mitochondria in children, as Bell *et al.* (1980) reported a similar mitochondrion-to-muscle fiber ratio in prepubertal and adult muscle tissues.

Carbohydrate ingestion during exercise

Carbohydrate feeding during exercise has been extensively studied in order to find solutions to spare muscle glycogen, maintain a high rate of carbohydrate oxidation and reduce or delay fatigue. CHO ingested can represent a substantial source of energy. Riddell *et al.* (2001) have shown that the intermittent ingestion of a solution of glucose and fructose during a 90-minute cycling exercise at 55 percent VO_2max, followed by a test at 90 percent VO_2max until exhaustion, was associated with a mean time to exhaustion of 202 seconds when children were fed, whereas it was only 142 seconds when children drank only water. In fact, perhaps due to their lower endogenous glycogen stores, carbohydrate feeding during exercise in children may be of more benefit to children than to mature subjects. Timmons *et al.* (2003) have shown that during a 60-minute cycling exercise at 70 percent VO_2max, exogenous glucose contributed 22 percent of total energy expenditure in children and 15 percent in adults. In theory, this increase in energy contribution from carbohydrate feeding should lead to a greater improvement in performance.

Nutritional considerations

The amount of energy and protein needed per kg of body mass decreases with age, but the total amount of each increases as body size increases. For example, the average 2-year-old needs about 1000 kcal and 13 grams of protein per day. By age 6, that child will need about 1600 kcal and 19 grams of protein per day (Institute of Medicine, Food and Nutrition Board 2002). Energy and protein needs increase during childhood owing to periods of rapid growth and the formation of muscle, blood, and bone, which require high levels of anabolic metabolism. Those needs will be even greater for physically active children. Appendix D provides formulas that may be used to estimate a child's energy

needs for proper growth and development. These formulas take body mass, height, and activity levels into account.

Carbohydrate recommendations for children are the same as those for adults: 45 to 65 percent of energy intake. As in the adult diet, most of the carbohydrate in a child's diet should be from wholegrains, fruits, and vegetables. These will provide the recommended amount of fiber. For children, an adequate level has been established based on data that show an intake of 14 grams of fiber per 1000 kcal reduces the risk of heart disease. Infants need a high-fat diet (40 to 55 percent of energy intake) to support their rapid growth and development, but by age 4 the recommended proportion of kcal from fat is reduced to provide adequate energy without increasing the risk for developing chronic disease. The acceptable range for fat intake is 30 to 40 percent of energy intake for children aged 1 to 3 years and 25 to 35 percent of energy for those aged 4 through 18 years compared to 20 to 35 percent for adults (Institute of Medicine, Food and Nutrition Board, 2002). The diets of children over the age of 3 should also be low in cholesterol, saturate fat, and trans-fat to reduce the risk for developing heart diseases.

Children and adolescents are smaller than adults, and for the most part the recommended amounts of micronutrients are also smaller. Generally, a well-planned diet that follows the professional recommendations for children will meet needs. For example, consuming the recommended amount of meats and wholegrains helps ensure enough vitamin Bs. Adequate consumption of fruits and vegetables provides sufficient vitamin C and vitamin A. Milk and dairy products provide calcium and vitamin D and vitamin A. Fortified breakfast cereals help compensate for poorer diets by providing the recommended amounts of a variety of micronutrients in a single serving. It must be noted that despite the relative abundance of nutrients in modern diets, many children are still at risk for deficiencies of calcium, vitamin D, and iron due to poor food choices.

Insulin resistance

Insulin is an anabolic hormone that promotes cellular glucose uptake and synthesis of glycogen and triglycerides. Insulin resistance is defined as the decreased ability of insulin to stimulate cellular glucose uptake and storage and to suppress hepatic glucose production. This condition is also associated with the reduced ability of insulin to suppress fat mobilization and thus increase levels of circulating fatty acids. Insulin resistance is an important feature of non-insulin-dependent or type 2 diabetes, but it may also occur in individuals without type 2 diabetes, most of whom are obese. There is a strong correlation between **central obesity** and insulin resistance. Central obesity is when excessive fat around the stomach and abdomen builds up to the extent that it is likely to have a negative impact upon health. In addition to obesity, insulin resistance has also been linked to physical inactivity, poor diet, and oxidative stress.

Testing for insulin resistance

Insulin resistance may be assessed by using an oral glucose tolerance test. In this test, 75 to 100 g of glucose in water is given orally to a fasting subject. Blood levels of glucose and insulin are subsequently measured at intervals of two to three hours. During this measurement period, the blood level of glucose rises initially and then falls due to the action of insulin (Figure 12.3). The response curve for the blood level of insulin generally follows a similar but lagging time course. Insulin resistance is therefore judged from the insulin response compared to the glucose response. Those who demonstrate a high insulin response in the face of a normal or high glucose response will be considered insensitive to insulin or insulin resistant. Although simplistic, this technique has its

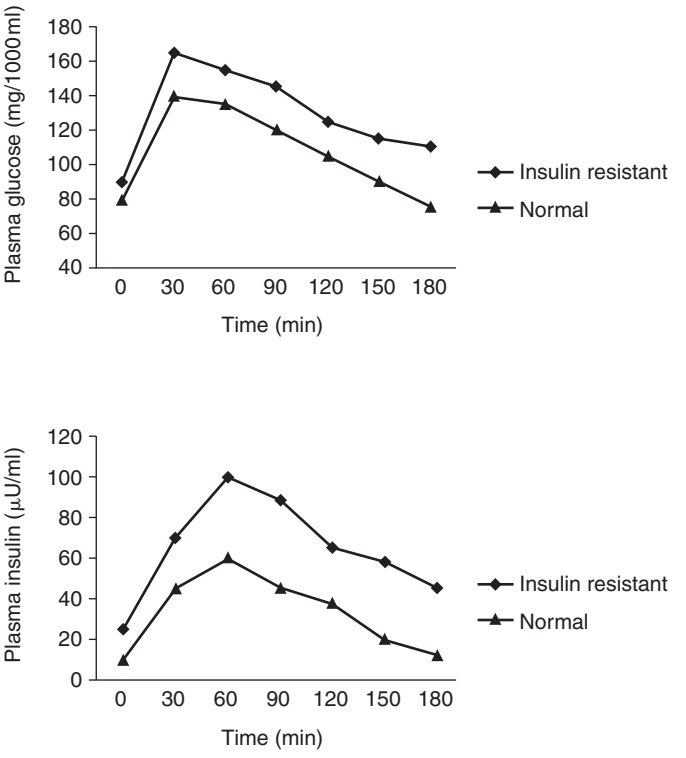


Figure 12.3 Sample plasma glucose and insulin responses during a three-hour oral glucose tolerance test before and after aerobic training

weakness in that it is difficult to interpret because blood glucose concentration depends not only on insulin sensitivity of the liver and peripheral tissues, but also on many other factors, such as glucose absorption, insulin secretion, and insulin clearance. In this test, concentrations of glucose and insulin are mutually interrelated, and changes in one variable can simultaneously result in changes in the other, and vice versa. Thus, a causal effect of insulin on glucose metabolism cannot be determined at least in a sequential manner.

The shortcomings associated with the oral glucose tolerance test have promoted the development of a more precise but invasive technique called a **euglycemic, hyperinsulinemic glucose clamp** (DeFronzo *et al.* 1979). With this technique, blood glucose concentration is kept constant by glucose infusion that is regulated according to repeated, rapid blood glucose measurement. The blood insulin concentration is initially raised and then maintained constant via a prime-continuous infusion of insulin. Under these steady-state conditions of euglycemia and hyperinsulinemia, the glucose infusion rate equals to glucose disposal or uptake by the cell, which may then be used to determine the severity of insulin resistance. This technique, if conducted in conjunction with indirect calorimetry or isotopic tracing technique, can also allow for partitioning the amount of glucose taken up by tissues into those being oxidized and those being stored. Such information is valuable in exploring cellular mechanisms that account for insulin resistance. The glucose clamp technique has been widely used in most clinical studies designed to investigate glucose metabolism at a given insulin concentration. With the

use of multiple levels of insulin concentration, it becomes possible to generate a dose–response relation between insulin concentration and its effect on glucose disposal, which allows for a more complete examination of insulin action (Figure 12.4). Two terms have been derived as a result of this analytic approach: **insulin sensitivity** and **insulin responsiveness**. Increased insulin sensitivity is defined as a reduction in the insulin concentration that produces half of the maximal response, whereas increased insulin responsiveness is defined as an increase in the maximal response to insulin.

Insulin resistance and body fat distribution

Insulin resistance is associated not only with the overall accumulation of fat in the body, but also how the body fat is distributed. There is considerable evidence suggesting that excess accumulation of fat in the upper body, or truncal region, is a strong predictor of insulin resistance. For example, Banerji *et al.* (1995) observed that variance in **visceral** adiposity accounted for much of the inter-individual variation in insulin resistance among individuals with type 2 diabetes. In addition, a weight loss intervention study conducted by Goodpaster *et al.* (1999) revealed that among non-diabetic obese subjects, the decrease in visceral adiposity was the body composition change that best predicted the improvement in insulin sensitivity following weight loss. Such a distinctive role of different patterns of fat distribution is also supported by several *in vitro* studies that have examined metabolic heterogeneity of adipose tissue (Richelsen *et al.* 1991, Jansson *et al.* 1990). The general experimental approach of these studies was to isolate adipose tissue from abdominal and lower body **subcutaneous** regions so that the lipolytic activity of adipose tissue may be compared between the two regions. Collectively, these studies revealed that adipose tissue from the abdominal region is metabolically more active and has a greater tendency to be broken down into free fatty acids. As free fatty acids formed due to lipolysis in this central region are directly released into the portal circulation, it is considered that in those with central obesity, their liver may have been exposed to high concentration of free fatty acids, which can ultimately decrease hepatic insulin sensitivity. An excess of fatty acids in the systemic circulation derived from the abdominal

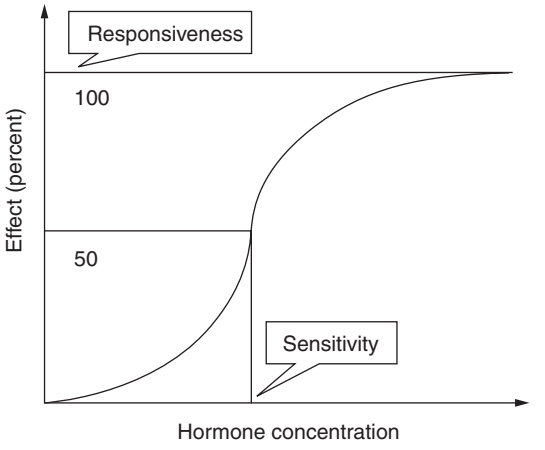


Figure 12.4 Hypothetical dose–response relation between hormone concentration and its biological effect. Insulin responsiveness is the maximal response of glucose disposal. Insulin sensitivity is the hormone concentration eliciting half of the responsiveness

region may also inhibit skeletal muscle glucose metabolism according to Randle *et al.* (1963), and this has been considered a cause of insulin resistance manifested in the peripheral region such as skeletal muscle.

There are other mechanisms proposed that link abdominal obesity with insulin resistance. The recognition of adipose tissue as a major secretory organ has led to the suggestion that visceral fat may release some factor that leads to systemic disturbances in metabolism. For example, it has been found that less leptin is secreted by visceral than by subcutaneous adipose tissue (Montague *et al.* 1998, Van Harmelen *et al.* 1998). **Leptin** is a satiety hormone that inhibits energy intake if fat tissue enlarges. If fat is deposited more in visceral than in subcutaneous depots, it could be argued that the lower leptin secretion from the visceral fat will lead to less effective responses to weight gain. Consequently, this may have some impact on insulin resistance. Visceral adipose tissue has also been found to secrete a number of cytokines, including interleukin-6 (IL-6) that are pro-inflammatory (Mohamed-Ali *et al.* 1998). It is believed that these substances via their entry into the portal vein can particularly impair the metabolic function of the liver and other surrounding tissues, thereby resulting in insulin resistance (Frayn 2000).

Subcutaneous adipose tissue in the legs is generally regarded as a relatively weak marker of insulin resistance. However, there are a growing number of studies that have attempted to examine the impact of peripheral adiposity on insulin resistance. Goodpaster *et al.* (2000) used computed tomography imaging to measure the quantity and distribution of adipose tissue in the thigh. Via a novel approach of subdividing adipose tissue into that present above the fascia lata (termed subcutaneous adipose tissue) and that present below the fascia lata (termed subfascial adipose tissue), these authors observed that variance in the amount of adipose tissue beneath muscle fascia correlated with insulin resistance, whereas no correlation was found between insulin sensitivity and the subcutaneous adiposity of the legs. These findings suggest that the amount of fat contained beneath the fascia as well as within the muscle tissue in the lower extremities is a key determinant of insulin resistance.

Effect of insulin resistance on glucose and fat utilization

Numerous studies have been conducted to examine mechanisms underlying the impairment in insulin-mediated glucose utilization seen in obese and NIDDM individuals. These studies have generally used the glucose clamp technique in conjunction with muscle sampling, indirect calroimetry, and/or the isotope tracer method so that metabolic fats of glucose taken by the skeletal muscle may be further divided into glucose oxidation, glucose storage, and non-oxidized glycolysis. This experimental approach allows the examination of mechanisms responsible for insulin resistance at the cellular level. An early study by DeFronzo *et al.* (1985) revealed an approximately 45 percent reduction in insulin-stimulated leg glucose uptake in non-obese diabetic subjects. Using obese diabetic subjects, Kelley *et al.* (1992) observed a 60 percent decrement in insulin-stimulated leg glucose uptake. Of this deficit of glucose uptake, 66 percent was due to decreased leg glucose storage, whereas 33 percent was due to decreased leg glucose oxidation. This finding, together with the fact that these patients had a lower than normal activities of glycogen synthase (Kelley *et al.* 1992), suggests that the reduced insulin-mediated glucose uptake can be attributed mainly to a decreased leg glucose storage. It is now widely believed that glycogen synthesis is the metabolic pathway in skeletal muscle most severely affected by insulin resistance and is primarily responsible for decreased rates of glucose utilization. From a practical standpoint, individuals with obesity and NIDDM are at disadvantage with regard to physical activity due to insulin resistance and its associated reduction in glycogen storage. These individuals may avoid performing sustained strenuous exercise that depends heavily on muscle glycogen as source of energy.

Reduced muscle glycogen content will lead to an increase in fat utilization in order to maintain adequate energy supply. This homeostatic adaptation has been well documented in healthy individuals. However, recent studies have suggested that the skeletal muscle in those with insulin resistance were unable to make such a switch easily from carbohydrate to fat utilization (Kelley 2005). In other words, as a result of insulin resistance fat utilization is also lower in addition to impaired glucose metabolism. This conclusion was derived from observations that during fasting conditions respiratory quotient (RQ) across the tissue bed of the leg was comparatively higher in people who were obese and insulin resistant than in metabolically healthy individuals. As mentioned earlier, a high RQ represents a greater reliance on carbohydrate oxidation. Recently, Ukropcova *et al.* (2005) found that fat oxidation of skeletal muscle increased in subjects with improved insulin sensitivity, leanness, and aerobic fitness. An inability to increase the reliance upon fat oxidation in the face of a reduced muscle glycogen has been termed **metabolic inflexibility**. As shown in Figure 12.5, healthy individuals use predominantly fat as a source of energy during fasting, but are able to shift efficiently to glucose oxidation upon insulin stimulation. However, those with obesity and NIDDM demonstrate a constrained adjustment to the transition between fasting and insulin-stimulation conditions. Their metabolic responses are blunted in terms of fat utilization during fasting and carbohydrate utilization upon insulin stimulation. The phenomenon of metabolic inflexibility emphasizes the importance of physical activity being a part of intervention for treating obesity and NIDDM. As discussed in Chapter 9, regular aerobic exercise training will increase the ability of skeletal muscle to oxidize fat and thus delay the consumption of glycogen.

Role of exercise in improving insulin sensitivity

Exercise can produce many favorable responses with respect to carbohydrate and fat metabolism. For example, glucose uptake by peripheral tissues such as muscle increases

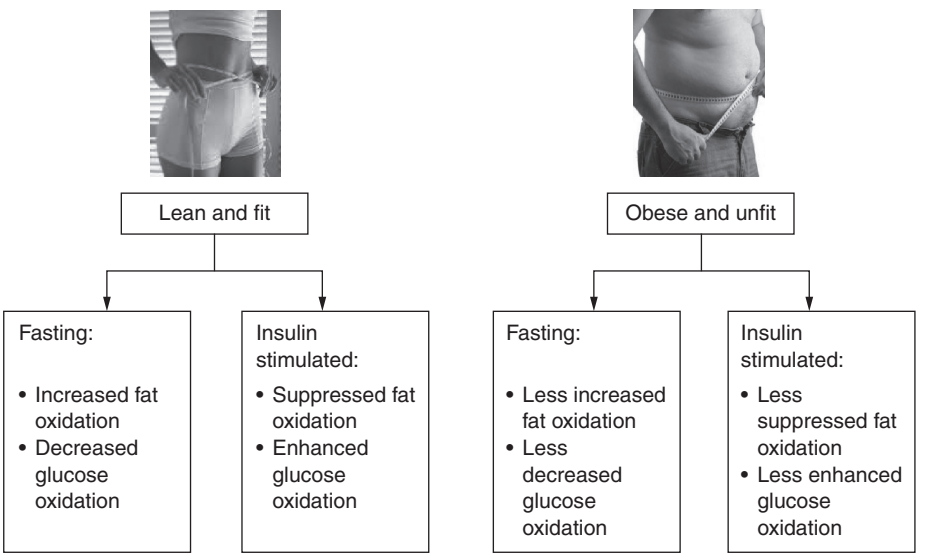


Figure 12.5 Schematics of metabolic inflexibility associated with insulin resistance

Source: adapted from Kelley (2005).

during exercise. Such an increase in glucose uptake helps correct hyperglycemia. Exercise also allows a greater utilization of fatty acids and thus is considered a relatively viable option for reversing insulin resistance. Because of these beneficial patterns of metabolism which clearly suggest the potential of exercise in treating or preventing metabolic diseases, there has been a growing stream of research that has attempted to directly examine both the acute and chronic effects exercise has on improving tissue's sensitivity to insulin.

Acute improvement in insulin-mediated glucose disposal

The impact of prior aerobic exercise upon subsequent insulin sensitivity or insulin-mediated glucose disposal has been typically examined using the euglycemic hyperinsulinemic glucose clamp. This procedure is often performed during the recovery period in order to examine the acute effect of prior exercise, although in some studies it occurred in the next day or so. With the selection of multiple levels of insulin to be infused, a dose–response curve can be generated between insulin concentrations and its resultant rates of glucose disposal in order to assess insulin sensitivity. It has been well documented that in healthy humans, insulin-mediated whole-body glucose disposal was increased following an acute bout of exercise and this improved insulin action remained for as long as 48 hours (Mikines *et al.* 1988, Richter *et al.* 1989). The improved insulin action following an acute bout of exercise has also been demonstrated in patients with NIDDM and obesity (Devlin and Horton 1985, Devlin *et al.* 1987, Burstein *et al.* 1990). These findings clearly support the use of aerobic exercise in treating insulin resistance.

Some of the aforementioned studies have used the clamp technique combined with indirect calorimetry and the isotopic tracer technique in an effort to delineate the metabolic fate of enhanced glucose uptake (Devlin and Horton 1985, Devlin *et al.* 1987). It was found that the exercise-induced improvement in insulin-mediated glucose disposal can be largely explained by an increase in glucose storage as glycogen. A handful of studies of both animals and humans also revealed an increase in glycogen synthase and hexokinase during exercise recovery. Collectively, it is plausible to conclude that glycogen formation is an ultimate destination for the augmented glucose taken up by muscle following exercise.

The improved insulin action following exercise may also be ascribed to an augmented glucose transport across the cell membrane. Glucose transport into tissues is achieved by the action of protein molecules called glucose transporters. As mentioned earlier, a number of different glucose transport proteins have been identified and they are manifested in a variety of different tissues. GLUT 4 is the form of transporter found in skeletal muscle and adipose tissues. In a series of experiments using diabetic rats, Richter *et al.* (1982, 1984, 1985) found an acute increase in glucose transport following exercise. In these studies, glucose transport was determined by quantifying how much of the specially marked glucose (i.e., 3-O-methylglucose) entered the muscle cell. Ren *et al.* (1994) also observed an increase in GLUT 4 expression along with an improved insulin stimulated glycogen storage in rat muscle following prolonged swimming. It appears that the improvement in insulin action occurs primarily in exercising muscle. Since exercise is also accompanied by major cardiovascular and hormonal changes, it is possible that insulin action is also affected in tissues other than muscles. Recent studies have shown that the liver, like muscle, becomes more insulin sensitive following exercise (Pencek *et al.* 2003). Like muscle, a major portion of glucose taken up by the liver is also channeled into liver glycogen synthesis (Hamilton *et al.* 1996).

As glycogen synthesis represents a major metabolic fate for enhanced glucose uptake, it may be speculated that the greater the depletion of glycogen during prior exercise,

the greater the improvement in insulin sensitivity following exercise. However, this hypothesis remains questionable. It has been found that improved insulin effect on glucose uptake can persist even when pre-exercise glycogen levels have been restored (Hamilton *et al.* 1996, Richter 1996). This finding suggests that this exercise benefit is not necessarily dependent on glycogen depletion. On the other hand, there are several lines of research that appear to support this hypothesis. For example, Bogardus *et al.* (1983) and Ivy *et al.* (1985) found an inverse relation between insulin sensitivity and muscle glycogen content following a single bout of exercise. Using a glucose tolerance test, Kang *et al.* (1996) also reported improved insulin action following exercise at 70 percent but not 50 percent VO_2max. It may be safe to suggest that if an exercise program is prescribed with a goal of improving insulin sensitivity, then this program should entail at least some component of vigorous exercise.

Chronic changes resulting from physical training

Physical training consists of repeated bouts of acute exercise. With the use of an oral glucose tolerance test, studies that compare trained and untrained individuals have shown that trained individuals are better able to tolerate glucose and are more sensitive to insulin (King *et al.* 1987, Heath *et al.* 1983, Seals *et al.* 1984). This benefit associated with training was also agreed by studies using the hyperinsulinemic glucose clamp technique, although it is of interest that these studies demonstrated an improved insulin responsiveness, but not insulin sensitivity (Mikines *et al.* 1989a, 1989b). Remember that insulin responsiveness represents the maximal ability of the whole body to handle glucose and as such an improvement in this measure may be owing to wider changes that occur not only in skeletal muscle, but also in the liver, adipose tissue, and pancreas. Exercise training has been found to increase muscle GLUT 4 expression (Lee *et al.* 2002, Terada *et al.* 2001). This increase in GLUT 4 may have contributed to the enhanced capacity for insulin-stimulated glucose disposal in trained subjects. The training-induced improvement in insulin action may also be due to the fact that trained subjects are able to utilize more of their fat energy sources. This augmented fat utilization may be in part because of increased lipolysis. It was found that training can make adipose tissue more sensitive to adrenergic stimulation (Izawa *et al.* 1991). As discussed earlier, insulin resistance is linked to abdominal obesity as well as to an excess accumulation of intramuscular triglyceride. It was also found that training would result in a decrease in the mRNA for proinsulin and glucokinase in the pancreas (Koranyi *et al.* 1991). A reduction in these protein molecules suggests a decreased insulin secretion at a given level of blood glucose concentration.

Nutrition considerations

The primary cause of insulin resistance is excess body weight, especially excess fat around the waist. Fortunately, weight loss can help the body respond better to insulin. Research indicates that people with insulin resistance and prediabetes can often prevent or delay developing diabetes by normalizing their body weight and body composition. Various dietary interventions aimed to reduce dietary intake and to achieve a negative caloric balance are discussed in Chapter 15 which deals with energy balance and weight control. Another important approach to reversing insulin resistance is to control blood glucose concentrations by restricting their carbohydrate intake. Readers are referred to the following section in which more specific dietary recommendations aimed to treat or prevent diabetes are provided.

Diabetes mellitus

Diabetes mellitus is defined as abnormally high levels of blood glucose due to the inability to manufacture or respond to insulin. Worldwide, 100 to 120 million people have this chronic condition. In the US, its prevalence currently stands at about 16 million people, nearly half of whom do not yet know they have the disease.

Insulin-dependent and non-insulin-dependent diabetes mellitus

The major types of diabetes are insulin-dependent diabetes mellitus (IDDM) and non-insulin-dependent diabetes mellitus (NIDDM). IDDM, also called type 1 diabetes, usually emerges before the age of 30, and tends to come on suddenly. NIDDM, also referred to as type 2 diabetes, is far more common than IDDM. It usually starts after the age of 30, and the majority of those who have the disease are obese. Recently, there has been a steady increase in cases in which those who are younger (<30 years of age) are also diagnosed with NIDDM, particularly if they are overweight. The onset of NIDDM tends to be more gradual than that of IDDM, and blood glucose levels remain more stable.

IDDM is an autoimmune disease in which the body produces antibodies that attack and damage the pancreatic beta cells. At first, the ability of the beta cells to secrete insulin is merely impaired, but usually within a year or so these cells stop producing or produce little insulin. People with IDDM must inject insulin daily as their function of body tissues in responding to insulin remains normal. Although heredity plays some role in IDDM, there is no known family history of diabetes in most cases.

NIDDM, on the other hand, begins with the impairment of the body's tissues in responding to insulin. Therefore, in order to get cells the glucose they need, the beta cells must increase their production of insulin. Diabetes results when the beta cells are unable to secrete enough extra insulin to overcome the tissue's resistance to insulin. Most people with NIDDM can be treated with oral drugs aimed to improve insulin sensitivity or simply with lifestyle intervention that promotes weight loss. About 30 to 40 percent of NIDDM patients need insulin to achieve adequate control of their blood glucose. Heredity plays an important role in NIDDM and those with NIDDM are highly probable to have at least one relative with diabetes.

Cellular defects in glucose metabolism

Diabetes is regarded as a metabolic disorder in that it impairs the way the body utilizes glucose due to a deficiency of insulin. Each cell needs a regular supply of glucose. The cells absorb glucose from the blood and use some of it immediately for various metabolic functions. The rest of the glucose is converted into glycogen in the liver and muscles and stored there for future use. However, the body's ability to store glycogen is limited, and glucose that is not used immediately or stored as glycogen will be converted into triglycerides stored in adipose tissue. Insulin is the key regulator of glucose in the body. As blood glucose levels rise such as after a meal, the pancreas produces insulin, which is then transported via circulation to target organs such as the muscles and liver. Insulin then attaches to sites on the surface of cells called receptors. Binding of insulin to these receptors causes carrier proteins or **glucose transporters** to move from inside the cell to the cell's surface. Glucose transporters travel back and forth across the cell membrane picking up glucose from the blood and dropping it off inside the cell. In diabetes, insufficient insulin production or tissues' insensitivity to insulin results in elevated blood glucose, which, if it remains uncontrolled, can cause many chronic complications, including cardiovascular diseases, kidney damage, neuropathy, and diabetic foot.

Glucose transporters (GLUT) are a family of membrane proteins found in most mammalian cells that are responsible for transporting glucose across cell membrane. There have been multiple isoforms of glucose transporter proteins (i.e., GLUT 1, GLUT 2, GLUT 3, GLUT 4, etc.) being identified and they are distributed differently throughout different body tissues. Much of the research in this area has been related to GLUT 4 in part because they are found primarily in skeletal muscle, which is considered a major depot for storing carbohydrate. In addition, unlike other glucose transporters, the function of GLUT 4 can be affected by insulin. The working mechanism of glucose transporters remains hypothetical at this point. It is thought that the binding of insulin to its receptors on the cell membrane triggers a series of events involving second messengers that lead to translocation of GLUT 4 from inside the cell to the cell surface. These GLUT 4 proteins then bind with glucose molecules, and such binding provokes a conformational change associated with transport and thus releases glucose to the other side of the membrane (Hebert and Carruthers 1992, Cloherty *et al.* 1995).

Metabolism during exercise

Exercise has long been regarded as a beneficial treatment of diabetes. However, it is only recently that the interaction between exercise and these metabolic disorders has been studied extensively. Research in this area has served to provide inside knowledge to the unique characteristics of exercise responses related to these metabolic disorders. This information will ultimately help in developing an effective exercise program aimed at treating or preventing diabetes.

Blood glucose

In those early investigations that used patients with IDDM, it was generally found that a bout of aerobic exercise will cause a fall in blood glucose to a normal level if these patients had been treated regularly with insulin and had mild hyperglycemia. This observation suggests that regular exercise training may be an effective aid to glucose regulation. Plasma glucose concentration reflects a balance between glucose uptake by peripheral tissues, mostly muscles, and glucose production by the liver. Wahren *et al.* (1975) found that in insulin-withdrawn diabetic subjects, muscle glucose uptake was greater, while hepatic glucose production was similar as compared to healthy controls during exercise. According to the authors this greater glucose uptake seen in IDDM was primarily driven by the mass action of hyperglycemia. Consequently, more glucose can rush into tissue due to greater concentration gradients. In these patients, it is the lack of insulin that prevents their tissues from drawing glucose from blood successfully. However, muscle contraction can allow this desired response to occur. The glucose-lowering effect of exercise, however, was not always the case especially in patients with more severe conditions of IDDM. It was found that patients with more marked hyperglycemia may respond to exercise with a further rise in blood glucose levels (Wahren *et al.* 1978).

Within the past few decades, considerable efforts have also been devoted to examining blood glucose responses during exercise in patients with NIDDM. The favorable glycemic response as seen in IDDM was also observed in NIDDM. In addition, the mechanism underlying this response appears to be similar. Researchers have observed that in NIDDM a fall in blood glucose during exercise was accompanied by increased peripheral glucose uptake, whereas hepatic glucose production remained the same between diabetics and healthy controls (Colberg *et al.* 1996, Kang *et al.* 1999, Martin *et al.* 1995). NIDDM is characterized by marked insulin resistance in skeletal muscle. The

greater increase in glucose uptake seen in NIDDM suggests that insulin resistance does not substantially impede the cellular uptake of blood glucose during exercise. In fact, it seems possible that muscle contraction abetted by the hyperglycemia and hyperinsulinemia is able to provide an additive or synergistic effect on glucose uptake. This contention may be underscored by the findings of DeFronzo *et al.* (1981), who reported that exercise in combination with experimentally induced hyperinsulinemia produced glucose uptake that was greater than that following either treatment alone in nondiabetic individuals.

Muscle glycogen

Muscle glycogen represents a major depot of energy source during exercise and its utilization increases as exercise intensity increases. Earlier studies using IDDM subjects have shown that the rates of glycogen utilization during exercise are no different in diabetics as compared with healthy controls (Saltin *et al.* 1979, Maehlum *et al.* 1977). Furthermore, the glycogen depletion pattern in the different fiber types during exercise is also similar in diabetics and healthy controls (Saltin *et al.* 1979). However, there is some indirect evidence to suggest that patients with IDDM may use less muscle glycogen. This contention was derived from the observation that diabetics had reduced rates of total carbohydrate oxidation concomitant with increased rates of muscle glucose uptake and was based on the assumption that all glucose molecules taken up by muscle are oxidized. Resynthesis of muscle glycogen during post-exercise recovery is an insulin-dependent process. Maehlum *et al.* (1977) found that in the absence of insulin injection, muscle glycogen repletion during recovery following exercise is minimal in diabetic patients, while with insulin, the rate of repletion is the same as in healthy subjects.

The reduced ability of skeletal muscle to use glycogen during exercise has been more uniformly reported in patients with NIDDM and obesity (Colberg *et al.* 1996, Kang *et al.* 1999, Goodpaster *et al.* 2002). By having three groups of healthy, obese, and NIDDM subjects exercise at a mild intensity, Colberg *et al.* (1996) found that while utilization of glycogen was lower in both the obese and NIDDM groups, it was only half as much in NIDDM as compared with that in healthy controls. This finding was confirmed by Kang *et al.* (1999) and Goodpaster *et al.* (2002) who used patients with NIDDM and obesity, respectively. To date, it remains uncertain as to what may have caused this reduced glycogen utilization to occur. In these studies, muscle glycogen was determined indirectly by subtracting the rate of glucose uptake from the rate of total carbohydrate oxidation and a decrease in muscle glycogen utilization was accompanied by an increase in plasma glucose uptake. In this context, it is possible that this reduced utilization of muscle glycogen may be secondary to a compensatory response resulting from greater glucose utilization. Both NIDDM and obesity have been associated with lower muscle glycogen content. Therefore, it is also likely that the reduced utilization of muscle glycogen during exercise may be brought about by lower muscle glycogen content prior to exercise.

Fatty acids and triglycerides

Circulating fatty acids and intramuscular triglycerides are the two major sources of fat energy utilized during exercise. Studies in exercising men have estimated that intramuscular triglycerides generally contribute more to the total fat oxidation than circulating fatty acids. However, circulating fatty acids will become more important oxidative fuels during prolonged exercise. The relationship between intramuscular triglycerides and circulating fatty acids appears to resemble that of muscle glycogen and plasma glucose; that is, while the intramuscular substrate stores are relatively more important at the start

of the work, fuels supplied via blood are the predominant substrates during prolonged work. In patients with IDDM in which insulin is completely absent, Wahren *et al.* (1984) found a greater increase in fat oxidation during exercise as compared to healthy controls. These authors also observed a more exaggerated exercise-induced rise in plasma norepinephrine. Norepinephrine is a lipolytic hormone that helps mobilize fatty acids from adipose tissue. In this regard, it is thought that the increased fat oxidation seen in patients with IDDM may be owing to increased lipolysis occurring in adipose tissue. The utilization of intramuscular sources of triglycerides was also found to be higher in a diabetic state. This finding was reported by studies using both IDDM patients and depancreatized dogs (Standl *et al.* 1980, Issekutz and Paul 1968).

More recently, greater fat oxidation was also reported during exercise in patients with NIDDM and obesity (Goodpaster *et al.* 2002, Horowitz and Klein 2000, Blaak *et al.* 2000). However, this increased fat oxidation can only be explained by increased oxidation of intramuscular triglycerides, because oxidation of blood-borne fatty acids was found to be either lower or the same in NIDDM or obese patients as compared to healthy controls. The greater utilization of intramuscular sources of fat has been attributed to an increased accumulation of intramuscular triglycerides frequently found in these patients during **post-absorptive state** and considered a cause of insulin resistance. Post-absorptive state is the period during which the gastrointestinal tract, such as the stomach and small intestine, is empty of nutrients and body stores must supply the required energy. It appears that patients with NIDDM or obesity are generally not limited in their ability to oxidize fatty acids during exercise, although they tend to accumulate excessive intramuscular triglycerides. Given that intramuscular triglycerides have been related to insulin resistance, exercise is considered quite ideal and necessary for these patients in that it can help stimulate a greater fat utilization and, in the case of NIDDM and obesity, may help alleviate or prevent insulin resistance. Table 12.7 provides a summary of altered carbohydrate and fat utilization in patients with IDDM and NIDDM.

Nutritional considerations

To help control blood glucose levels, people with diabetes should consume meals and snacks at regular intervals each day. This will ensure that the body maintains a consistent amount of glucose in the blood. The type of carbohydrate is also important. Complex carbohydrates are better than simple carbohydrates in that they provide sustained energy. Wholegrain products provide more nutrients and fiber. Wholegrain products as well as foods rich in protein and fat also have a low glycemic index that can avoid a surge in blood glucose levels upon consumption. Diabetes should incorporate the following tips into their dietary planning.

Table 12.7 Substrate utilization during aerobic exercise in patients with IDDM and NIDDM as compared to healthy controls

Substrate	*IDDM*	*NIDDM*
Carbohydrate		
Muscle glycogen	Same	Decreased
Plasma glucose	Increased	Increased
Fat		
Muscle triglycerides	Increased	Increased
Plasma fatty acids	Increased	Decreased/same

- Limit carbohydrates: Although all carbohydrates can be incorporated into carbohydrate counting, for good health, carbohydrates from vegetables, fruits, wholegrains, legumes, and dairy products take priority over other carbohydrate sources, especially those that contain added fats, sugars, or sodium. When it comes to grain flour products, it is best to consume grains in their whole form instead of flour form because flour tends to increase insulin resistance.
- Avoid sweetened beverages: All types of sugars are capable of raising blood sugar levels and contributing to insulin resistance. Sugar-sweetened beverages that should be avoided include soft drinks, fruit drinks, iced tea, and energy and vitamin water drinks containing sucrose, high fructose corn syrup, fruit juice concentrates, and other artificial sweeteners. Instead of drinking sweetened beverages, stick with water, seltzer, herbal or black tea, and coffee. When it comes to adding sweeteners to your beverages, or food, choose natural sweeteners like raw honey, organic stevia, dates, pure maple syrup, or blackstrap molasses.
- Eat more fiber: Consuming high-fiber foods like artichokes, peas, acorn squash, Brussels sprouts, avocado, legumes and beans, flaxseeds, chia seeds, and quinoa helps regulate blood glucose concentrations in diabetics. Load the plate with fresh vegetables as often as possible – they're high in fiber, low in calories, and contain an array of vitamins and minerals with anti-inflammatory properties.
- Eat healthy fats: The types of fatty acids consumed are more important than total fat in the diet. Individuals with insulin resistance are encouraged to select unsaturated fats in place of saturated and trans fatty acids. To prevent insulin resistance and diabetes, it is suggested that saturated fat intake be less than 7 percent of total energy intake per day. The intake of foods rich in monounsaturated fatty acids, such as olive oil, avocados, nuts, and seeds, can improve glycemic control. People with insulin resistance should also increase foods containing omega-3 fatty acids, specifically by eating at least two servings of wild-caught fatty fish every week that includes salmon, herring, tuna, white fish, and sardines. Foods rich in omega-3 are also listed in Chapter 3.
- Get enough protein: The consumption of higher amounts of protein during dietary treatment of obesity may result in greater weight loss than with lower amounts of protein. Researchers indicate that adequate dietary protein intake is of specific importance for people with insulin resistance and type 2 diabetes because proteins are relatively neutral about glucose and lipid metabolism, and they preserve muscle and bone mass, which may be decreased in people with poorly controlled insulin resistance. Lean protein foods are desirable in regulating blood sugar levels and they include organic chicken, wild fish, free-range eggs, lentils, yogurt, and almonds.

Summary

- In comparison with men, women are able to derive proportionately more of the total energy expended from fat oxidation during aerobic exercise. This gender difference may be attributed to the experimental observations that estrogen stimulates lipolysis and also inhibits carbohydrate utilization.
- Due to an increase in body mass including fetal tissue, there is an increase in energy cost during weight-bearing activities such as walking, jogging, and running in pregnant women. Their energy cost during non-exercise periods also increases due primarily to an increase in resting metabolism.
- The inhibitive effect of estrogen as well as other placental hormones on carbohydrate metabolism has placed pregnant women at high risk for developing insulin resistance that can lead to gestational diabetes. As such, being physically active

during pregnancy is of importance in preventing the occurrence of these metabolic disorders and this can be achieved by choosing primarily non-weight-bearing activities and exercising at low to moderate intensity.

- Both carbohydrate and fat utilization decrease as one ages and these declines can impair the ability of the elderly to tolerate strenuous physical activity. The age-related reduction in substrate utilization is due to the loss of the size and/or oxidative capacity of metabolically active tissues such as skeletal muscle as well as a decrease in tissues' sensitivity to insulin.
- Children and adolescents should not be regarded as miniature adults because the age-related functional deficiency in children and adolescents is not always attributable to the fact that they are smaller in size. Many differences in function have been found to be either partially related to or completely independent of changes in size.
- In comparison with adults, children are inefficient metabolically due to the fact that they are less coordinated in performing physical activities. They are also less able to store and use carbohydrate as an energy source and this can limit their tolerance to a strenuous exercise for an extended period of time. However, children have a lower oxygen deficit and they are also able to derive proportionately more of their total energy from fat oxidation.
- Insulin resistance is associated with an impaired utilization of intramuscular triglycerides. However, those with insulin resistance are not limited in their ability to use fat as an energy source during exercise. Therefore, exercise is considered relatively ideal in that it can help stimulate greater fat utilization, which may alleviate insulin resistance.
- Research has evidenced that a greater reduction in muscle glycogen following an acute bout of exercise can produce a greater improvement in insulin sensitivity. It may be safe to suggest that if an exercise program is prescribed with the goal of improving insulin sensitivity, then this program should entail at least some component of vigorous exercise so that a greater utilization of muscle glycogen can provide a positive impact upon insulin sensitivity.
- Regular physical activity has proven beneficial in improving insulin sensitivity. The improved insulin action may be explained by cellular changes, including increased glucose transporters and activity of enzymes that are responsible for glycogen synthesis. The improved insulin sensitivity is not only observed in skeletal muscle, but is also manifested in the liver and adipose tissue. These positive changes justify the use of exercise as part of therapy in treating insulin resistance associated with obesity and NIDDM.
- In healthy individuals, reduced muscle glycogen content will result in an increase in fat utilization. However, the skeletal muscle in those with insulin resistance is unable to make such a switch easily from carbohydrate to fat utilization. This condition is also known as metabolic inflexibility.
- Both IDDM and NIDDM are characterized as a metabolic disorder in that it impairs the body's ability to regulate blood glucose concentration and is accompanied by a condition of hyperglycemia. However, the etiology to this impairment is different. IDDM is associated with a lack of insulin. NIDDM involves a reduced ability of tissues to respond to insulin.
- Many individuals with obesity and NIDDM are characterized as having insulin resistance. Insulin resistance is defined as the decreased ability of insulin to stimulate cellular glucose uptake and storage and to suppress hepatic glucose production. Insulin resistance is not only associated with an overall level of body fat, but also with body fat distribution. Those obese individuals with their body fat being distributed primarily in the abdominal region are most prone to the condition of insulin resistance.

- Aerobic exercise helps reduce blood glucose levels of diabetic individuals. This blood-lowering effect of exercise can occur with and without insulin. For both IDDM and NIDDM, the introduction of an exercise program should be accompanied by accordant modifications of diet as well as by medication or insulin so that an over-reduction in blood glucose concentration or hypoglycemia may be prevented.

Case study: exercise training for type 2 diabetes

Julia is a 50-year-old sedentary, African-American woman who has had type 2 diabetes for five years. Julia's baseline weight is 160 pounds, and her waist circumference is 99 cm. Resting blood pressure is 144/68 mmHg. She is currently taking medication to lower her blood glucose concentrations. As recommended by her family physician, Julia plans to enroll in a three-month supervised aerobic exercise program. She received clearance from her physician before beginning exercise training.

Baseline laboratory analyses reveal a fasting blood glucose of 246 mg/100 ml, A1C of 9.9 percent, total cholesterol of 205 mg/100 ml, LDL cholesterol of 145 mg/100 ml, and total cholesterol-to-HDL cholesterol ratio of 4.8. Her VO_2max is 26.5 ml/kg/min and her percentage of body fat is 40.

Questions

- How would you describe Julia's results of baseline laboratory analyses in terms of blood chemistry, fitness, and body composition?
- What risk factors does Julia have that may contribute to cardiovascular diseases?
- How might regular exercise training benefit her diabetic condition?
- What type of exercise program should be prescribed for Julia?

Review questions

1 Describe the gender difference in fat utilization during exercise. What is the experimental evidence to support this gender difference?
2 What is the role estrogen plays in regulating fat and carbohydrate utilization?
3 Pregnant women have an increased risk of developing hyperglycemia and gestational diabetes. How do these conditions come about?
4 What are the benefits of regular exercise during pregnancy?
5 Define the term sarcopenia. Discuss the importance of maintaining lean body mass (i.e., muscle mass) as one ages.
6 Provide a specific explanation as to why there is an impaired utilization of carbohydrate and fat in older individuals.
7 Provide specific metabolic explanations for why older individuals tend to gain weight.
8 How are children different from adults in terms of their aerobic and anaerobic capacity as well as their ability to use fat and carbohydrate?
9 How would you explain the notion that children and adolescents should not be viewed as miniature adults?
10 Define the term insulin resistance. What are the symptoms associated with insulin resistance?
11 Why is there a close relationship between insulin resistance and visceral adiposity?
12 Insulin sensitivity can be assessed by an oral glucose tolerance test or a hyperinsulinemic-euglycemic glucose clamp test. How is each test administered? What are the advantages and disadvantages associated with each test?

13 Explain how insulin sensitivity is determined based on the results of a hyperinsulinemic euglycemic glucose clamp test.
14 Define the term metabolic inflexibility. Explain this condition using RQ values measured under the fast and fed conditions.
15 What are the health problems associated with metabolic inflexibility?
16 How does an improvement in insulin sensitivity come about following training?
17 What are the differences between insulin-dependent diabetes mellitus (IDDM) and non-insulin-dependent mellitus (NIDDM)?
18 What are the food choices that diabetics should adhere to in order to better manage their blood glucose concentration?

Suggested reading

1 Bar-Or O, Rowland TW (2004) Physiologic and perceptual responses to exercise in healthy children. In *Pediatric Exercise Medicine*. Champaign, IL: Human Kinetics, pp. 3–59.
This section of the book presents comparative data, demonstrating how the exercise-induced cardiorespiratory, metabolic, and perceptual responses differ among children and adults. It is clear that children are not miniature adults and some of the responses are specific to their biological age rather than to their body size.
2 Elia M, Ritz P, Stubbs RJ (2000) Total energy expenditure in the elderly. *European Journal of Clinical Nutrition*, 54: S92–S103.
Using doubly labeled water measurements and cross-sectional comparisons of different age groups, authors are able to examine how aging may affect the total energy expenditure and its sub-components, including resting metabolic rate and physical activity.
3 Goodpaster BH, Wolfe RR, Kelley DE (2002) Effect of obesity on substrate utilization during exercise. *Obesity Research*, 10: 575–584.
This original investigation provides strong evidence that characterizes substrate utilization patterns during exercise between obese and lean individuals.
4 Ivy JL (1997) Role of exercise training in the prevention and treatment of insulin resistance and non-insulin-dependent diabetes mellitus. *Sports Medicine*, 24: 321–336.
This review provides readers with further understanding of how physical training helps in treating and preventing insulin resistance and non-insulin-dependent diabetes. The cellular mechanisms responsible for improved insulin-mediated glucose disposal are thoroughly discussed.
5 Tarnopolsky MA (2000) Gender differences in substrate metabolism during endurance exercise. *Canadian Journal of Applied Physiology*, 25: 312–327.
This paper reviews both animal and human studies pertaining to gender differences in substrate utilization during endurance exercise. It also discusses the underlying mechanism for why such gender difference exists.

Glossary

Adolescence the period in which a child matures into an adult.
Central obesity a type of obesity in which excessive fat around the stomach and abdomen builds up to the extent that it is likely to have a negative impact upon health.
Childhood the phase of development in humans between infancy and adolescence.
Corpus luteum a yellow, progesterone-secreting mass of cells that forms from an ovarian follicle after the release of an ovum.
Estrogen a major female sex hormone produced primarily by the ovarian follicles and responsible for developing and maintaining secondary female sex characteristics and preparing the uterus for the reception of a fertilized egg.

Euglycemic a condition where blood glucose concentrations are within a normal range.

Exogenous arising from outside of an organism.

Follicular the phase during which follicles are formed during the menstrual cycle or the time period from onset of menstruation to ovulation.

Gestational diabetes a form of diabetes that occurs only during pregnancy.

Glucose tolerance the test that determines how quickly the ingested glucose is cleared from the blood.

Glucose transporters a family of membrane proteins found in most mammalian cells that function to transport glucose molecules across the cell membrane.

Hemoglobin the oxygen carrying protein in red blood cells.

Hyperinsulinemic glucose clamp a method that assesses how sensitive the tissue is to insulin and which requires maintaining a high insulin level by infusion with insulin.

Hyperlipidemia a condition where there is an abnormal elevation of blood lipids including cholesterol and triglycerides.

Indirect calorimetry a method which calculates heat produced by living organisms from their consumption of oxygen.

Infancy a stage of human development lasting from birth to approximately 2 years of age.

Insulin resistance a condition in which normal amounts of insulin are inadequate to produce a normal insulin response from fat, muscle, and liver cells.

Insulin responsiveness a measure of tissue's ability to respond to insulin and is determined as the peak rate of insulin-mediated glucose disposal using the euglyemic hyperinsulinemic clamp technique.

Insulin sensitivity a measure of tissues' ability to respond to insulin and may be determined as the insulin concentration that produces half of the maximal response in insulin-mediated glucose disposal using the euglyemic hyperinsulinemic clamp technique.

Leptin a satiety hormone from fat tissue that inhibits energy intake if fat tissue enlarges.

Lipoprotein lipase (LPL) an enzyme that cleaves one fatty acid from a triglyceride.

Luteal the phase during which corpus luteum secretes progesterone which prepares the uterus for the implantation of an embryo or the second half of the menstrual cycle from ovulation to the beginning of the next menstrual flow.

Metabolic inflexibility the inability to switch the utilization of lipids and carbohydrates in the peripheral tissue (i.e., muscle) based on substrate availability.

Oxygen deficit a lag of oxygen consumption at the onset of exercise and computed as the difference between oxygen uptake during early stages of exercise and during a similar duration in a steady state of exercise.

Oxygen kinetics a measure that assesses the integrated responses of oxygen requirements and supply at the onset of and during exercise of varying intensity.

Placenta a membranous vascular organ in the uterus developed during pregnancy and providing oxygen and nutrients for and transferring wastes from the developing fetus.

Placenta lactogen a polypeptide hormone that has similar structure and function to human growth hormone and is important in facilitating the energy supply of the fetus.

Post-absorptive state the time period when the gastrointestinal tract is empty and energy comes from the breakdown of the body's reserves such as glycogen and triglycerides.

Progesterone a steroid hormone that prepares the uterus for the fertilized ovum and maintains pregnancy.

Prolactin a peptide hormone secreted by the pituitary gland and associated primarily with lactation.

Puberty the period when children begin to mature biologically and become an adult capable of reproduction.

Respiratory exchange ratio a qualitative indicator of which fuel (carbohydrate or fat) is being metabolized to supply the body with energy.

Subcutaneous beneath or under the skin.

Testosterone a steroid hormone secreted by the testes that stimulates the development of male sex organs, secondary sexual traits, and sperm.

Thermogenesis the process by which the body generates heat or energy through metabolism.

Vastus lateralis the largest part of the Quadriceps muscle.

Visceral internal organs of the body, specifically those within the chest such as the heart and lungs or within the abdomen such as the liver, pancreas, or intestines.

13 Measurement of energy consumption and output

Contents

Key terms

- Acceleration
- Algorithm
- Creatinine
- Direct calorimetry
- Food diary
- Indirect calorimetry
- Missing foods
- Phantom foods
- Respiratory quotient
- Symptoms
- Accelerometer
- Caloric equivalent of oxygen
- Dietary history
- Doubly labeled water
- Food frequency questionnaires
- Isotope
- Pedometer
- Respiratory exchange ratio
- Signs

Assessing nutritional status

An assessment of nutritional status may include a comprehensive evaluation consisting of dietary analysis, physical examination, and anthropometric and laboratory assessments. Of these methods, measurement of nutrient intake via dietary analysis is probably the most widely used indirect indicator of nutritional status. Dietary analysis can measure total energy (calories), specific amounts of nutrients, and diversity. It allows researchers to analyze the patterns, quantity, and quality of food consumed by individuals or a population. It may also be used by researchers to try to associate dietary intake with risk for disease-related outcomes. Dietary analysis is used routinely in national nutrition surveys, epidemiologic or clinical studies, and various federal and state health and nutrition program evaluations.

Assessing dietary status includes taking into account the types and amounts of foods consumed and the intake of the nutrients and other components contained in foods. When the food consumption data are combined with information on the nutrient composition of food, the intake of particular nutrients and other food components can be estimated. Various methods for collecting food consumption data are available. However, no single best method exists. For example, the food consumption data can be obtained by observing all the food and drinks consumed by the individual for a specific period of time or by asking the individual to record or recall their intake. Neither option is ideal in that being observed can affect an individual's intake. Similarly, recording and recalling intake may be erroneous because these methods rely on the memory, reliability, and cognitive level of the consumer. It has been reported that a person who is attempting to lose weight may tend to report smaller portions than were actually eaten (Johansson *et al.* 1998). Despite these disadvantages, properly collected and analyzed dietary intake data have considerable values. For example, using dietary analysis has allowed us to assess the adequacy of dietary intakes of individuals and groups, to monitor trends in food and nutrient consumption, to study the relationship between diet and health, to establish food and nutrition regulations, and to evaluate the success and cost-effectiveness of nutrition and risk-reduction programs. The commonly used methods described below are the best tools available for evaluating dietary intake to predict nutrient deficiencies and excesses.

A 24-hour dietary recall

A 24-hour dietary recall is a structured interview intended to capture detailed information about all foods and beverages (and possibly dietary supplements) consumed by the respondent in the past 24 hours, generally from midnight to midnight the previous day. This method is most commonly used for assessing dietary intake. It involves a registered dietician or a trained interviewer asking people to recall exactly what they ate during the preceding 24-hour period. Occasionally, the time period is the previous eight hours, the past seven days, or, in rare instances, even the preceding month (Lee-Han *et al.* 1989). However, memories of intake may fade relatively quickly beyond the most recent day or two, so that loss of accuracy may exceed gain in representativeness.

Using this method, a detailed description of all food and drink, including descriptions of cooking methods and brand names of products, is recorded. The interviewer helps the respondent remember all that was consumed during a predetermined period and assists the respondent in estimating portion sizes of foods consumed. The method typically begins by asking what the respondent first ate or drank on last awakening. The recall proceeds from the morning of the present day to the current moment. The interviewer then begins at the point exactly 24 hours in the past and works forward to the

time of awakening. Some researchers use the time period from midnight to midnight of the previous day. Asking the respondent about his or her activities during the day and inquiring how those activities may have been associated with eating and drinking can help in recalling food intake. The recall may then be analyzed using a computerized diet analysis program.

The 24-hour recall has several advantages (Table 13.1). It may be conducted in person or by telephone with similar results. It is quick to administer (i.e., 30 minutes or less), and it can provide detailed information on specific foods, especially if brand names can be recalled (Block 1989). It requires only short-term memory. It is well received by respondents because they are not asked to keep records and their time and effort of involvement is relatively low. The method is also considered to be more objective than the methods of a food diary and food frequency questionnaire because its administration does not alter the usual diet (Guenther 1994). This method is considered appropriate for use with low-income and low-literacy populations because the subjects do not need to read or write to complete the recall.

Recalls have several limitations (Table 13.1). The primary limitation of this method is that data on a single day, no matter how accurate, are a poor representation of an individual's usual nutrient intake due to intra-individual variability. However, multiple 24-hour recalls performed on an individual and spaced over various seasons may provide a reasonable estimate of that person's usual nutrient intake. In a study that compared various methods of dietary assessment, a minimum of four repeated 24-hour recalls were found to be the most appropriate method of dietary assessment (Holmes *et al.* 2008). This method requires a trained interviewer, which may increase costs of the assessment. In addition, respondents may withhold or alter information about what they ate owing to poor memory or embarrassment, or trying to please or impress the interviewer. The items that respondents tend to under-report include binge eating, consumption of alcoholic beverages, and consumption of foods perceived as unhealthy. On the other hand, respondents tend to over-report consumption of name-brand foods, expensive cuts of meat, and foods considered healthy (Feskanich *et al.* 1993). Foods eaten but not reported are known as **missing foods**, while foods not eaten but reported are known as **phantom foods**.

Errors associated with under-reporting and over-reporting can be minimized by using the multiple-pass 24-hour recall method in which the interviewer and respondent review the previous day's eating events several times to obtain detailed and accurate information about food intake. For example, a brief list of foods eaten during the previous 24 hours is initially compiled. In the second pass, a detailed description of foods on the brief list is obtained by asking respondents to clarify the description and preparation methods of foods on this list. In the third pass, the interviewer reviews the data collected, probes for additional eating occasions, and clarifies portion sizes using standardized methodology.

Food diary or food intake record

Although the method of 24-hour recall is relatively simple, its usefulness depends on a person's memory and cooperation. To more accurately assess a person's diet, it is better to record foods and beverages while that person is consuming them. This method is called the **food diary** or food intake record. Using this method, the respondent records, at the time of consumption, the identity and amounts of all foods and beverages consumed over a period of time, usually ranging from two to seven days and including at least one weekend day, since most people eat differently on weekends than during the school or work week. Directions for conducting the food diary as well as recording samples may be found in Appendix G. Using this method, food and beverage consumption is determined by estimating portion size, using household measures, or weighing the food or beverage on

Table 13.1 Advantages and disadvantages of various methods assessing diet

Method	*Advantages*	*Disadvantages*
24-hour recall	• Quick and easy to administer • Requires only short-term memory • Does not alter eating patterns • Low respondent burden • Can provide detailed information on types of foods consumed • Useful in clinical settings	• Not representative of individual diet • Subject to under- or over-reporting of serving size • May omit foods • Relies on memory • Results vary with season • Data entry can be labor-intensive
Food diary or food intake record	• Provides detailed information on nutrient intake • Does not rely on memory • Multiple days of recording are more representative • Can provide data on eating habits	• Requires high degree of cooperation from respondents • Respondents must be literate • May alter diets • Labor-intensive and time-consuming in data analysis
Food frequency questionnaire	• Can be self-administered • Results are machine readable • Modest demand on respondents • Relatively inexpensive for a large sample size • May better represent usual intake than several days of food record or 24-hour recall • Helps reveal diet–disease relationship	• May not give a good estimate of quantity of foods consumed • Requires a good memory of diet over weeks and months • Data can be compromised when multiple foods are grouped within single listings
Dietary history	• Assesses usual eating habits, not just recent intake • Can detect seasonal changes • Data on all nutrients can be obtained • Can correlate well with biochemical measures	• Lengthy interview process • Requires highly skilled interviewers • Difficult to analyze • Requires cooperative respondent with ability to recall usual diet

the scales. Portion sizes are often quantified by using household measures such as cups, tablespoons, and a weight scale (Figure 13.1) or measurements made with a ruler. Certain items, such as eggs, apples, bananas, bread, or 12-oz cans of soft drinks, may be simply counted as units. The record should be as complete as possible, including not only food and beverages, but also dressings, condiments, brand names, and preparation methods. This method allows portion sizes to be estimated. Ideally, food and leftovers should be weighed so that results of analysis will be more accurate. However, using weighed food records requires a great deal of effort and cooperation from respondents and may be cost-prohibitive in terms of measurement scales.

One of the most important advantages of this method is that the food record does not depend on memory because the respondent ideally records food and beverage consumption at the time of eating (Table 13.1). In addition, data from a multiple-day food record is more representative of usual intake than that from a 24-hour recall or 1-day food record. However, it is recommended that such a food record is derived from non-consecutive, random days (including weekends) and that multiple food records should be carried out to cover different seasons (Rebro *et al.* 1998, Macdiarmid and Blundell 1997). Via the use of dietary software, this method also provides more detailed nutrient intake information that can be specific to each day or each meal. Results of analysis typically include the consumption of total calories, calories from macronutrients, dietary fiber, sodium, cholesterol, and saturated and unsaturated fat, all of which have been directly linked to health. Data outputs also include the consumption of essential nutrients, such as protein, vitamins, and most minerals, relative to the recommended daily allowance (RDA).

The food diary has several disadvantages (Table 13.1). The method requires respondents to be literate and cooperative, so that they are able and willing to spend the time and effort necessary to record their dietary intake for multiple days with care. In fact, it has been suggested that those who are able to complete this method may not be representative of the general population (Rebro *et al.* 1998). In some cases, the tedious nature of this method can discourage the respondent from continuing or cause the respondent to change his or her intake rather than record certain items. When asked directly about recording their food intake, 30 to 50 percent of respondents have reported changing their eating habits while keeping a food record (Macdiarmid and Blundell 1997). Therefore, it is likely that this method can lead to an under-reporting of energy and nutrient intake (Sawaya *et al.* 1996).

Food frequency questionnaires

Food frequency questionnaires assess energy or nutrient intake by determining how frequently an individual consumes a limited checklist of foods that are major sources of nutrients or of a particular dietary component in question. For example, how often do

Figure 13.1 Measuring tools commonly used in dietary analysis

you drink orange juice? How many times a week do you eat red meat? The foods included in the questionnaires are usually important contributors to the population's intake of energy and nutrients. They may focus on particular food groups, preparation methods, or nutrients. Respondents indicate how many times a day, week, month, or year they usually consume the foods. Depending on the type of dietary information needed, food frequency questionnaires may include questions about serving size. If only a general sense of serving size is needed, the respondent may be asked to indicate whether the servings were small, medium, or large relative to a standard serving. Some questionnaires may ask subjects to estimate serving sizes; these are called semi-quantitative. In terms of data analysis, a Scantron is often used so that respondents can mark their answers on an answer sheet, which can then be optically scanned and scored on a computer. This will save the researchers considerable time and effort, and makes food frequency questionnaires a cost-effective approach for measuring diet in large epidemiologic studies. For semi-quantitative questionnaires, quantities of nutrient intake can be estimated via computerized software programs that multiply the reported frequency of each food by the amount of nutrient in a serving of that food. Both the 24-hour recall and the food frequency questionnaire are often regarded as retrospective dietary assessment methods, which require the person to recall what he or she ate in the past. An example of food frequency questionnaire is illustrated in Figure 13.2.

Food frequency questionnaires have several advantages (Table 13.1). They place a modest demand on the time and effort of respondents and generate estimates of food

	Never	Once per week	2–4 per week	5–6 per week	Daily	Once per month	Once per 3 months	Once per year
Milk, yogurt, regular fat (1 cup)	○	○	○	○	○	○	○	○
Milk, yogurt, low-fat (1 cup)	○	○	○	○	○	○	○	○
Spinach, kale, other green leafy vegetables (1/2 cup)	○	○	○	○	○	○	○	○
Carrots (1 medium)	○	○	○	○	○	○	○	○
Beef (3 oz)	○	○	○	○	○	○	○	○
Rice, white (1 cup)	○	○	○	○	○	○	○	○
Rice, brown (1 cup)	○	○	○	○	○	○	○	○
Cookies (2–2" diameter)	○	○	○	○	○	○	○	○
Ice cream, regular fat (1/2 cup)	○	○	○	○	○	○	○	○

Figure 13.2 An example of a food frequency questionnaire

and nutrient intake that may be more representative of usual intake than a 24-hour recall or a few days of diet records. They are relatively easy and quick to administer, and the average time needed to complete the survey is usually less than 30 minutes. Although better data are obtained if an interviewer collects the data, the food frequency questionnaires may be self-administered and machine readable, and thus they are more cost-effective for use in studies that involve a large sample size. The questionnaires may be specific about foods or groups of foods to investigate the relationship between diet and disease. For example, if you are interested in the relationship between calcium intake and osteoporosis, you can assess calcium intake by the use of a food frequency questionnaire that asks only about foods high in calcium in subjects with and without a condition of osteoporosis.

There are some limitations associated with the food frequency questionnaire (Table 13.1). The most serious one is that it requires the subject to have a good memory of intakes over weeks, months, or sometimes years (Willett *et al.* 1985, Feskanich *et al.* 1993). This method provides qualitative data on types and frequencies of foods or food groups consumed over an extended period of time, although this limitation may be partially overcome by using a semi-quantitative questionnaire. In addition, the limited number of foods listed may cause the respondent to underestimate consumption, or the respondent may eat things that are not listed on the questionnaire. The food list varies depending on the questionnaire, but is usually limited to approximately 100 to 150 foods or drinks. Short questionnaires are faster and easier to administer but are likely to be less representative. On the other hand, long questionnaires may do a better job of assessing nutrient intake patterns, but can also be time-consuming and too tedious to complete.

Dietary history

Unlike the 24-hour recall and the food records, which assess recent intake for a short period, the **dietary history** is used to assess an individual's usual dietary intake over an extended period of time, usually a month to a year. This historical approach was initially developed by Burke in the 1940s. Burke's procedure involves four steps. The first is to collect general information about the respondent's health habits. The second step is to collect information on usual eating habits, such as the number of meals eaten per day, snacking patterns, likes and dislikes, and seasonal variation of eating patterns. This allows the interviewer to become acquainted with the respondent in ways that may be helpful in obtaining further information. At this step, a 24-hour recall is also collected. The third step is to collect information about the frequency of the consumption of specific foods. This step also serves as a check on the information given in step two. For example, the respondent may have said that he or she drinks an 8-oz glass of milk in the morning. The interviewer should then inquire about the participant's milk-drinking habits to clarify the information given about the respondent's milk intake. The fourth and final step is to ask the respondent to complete a three-day food record, which serves as an additional means of checking the usual intake. This last step is sometimes omitted, since it is only another measure of recent intake and it adds to the cost and time needed to complete the analysis.

The dietary history has several advantages over other methods of dietary assessment. It gives an overall picture of eating habits and patterns including seasonal changes, not just an estimate of recent intake. The method is one of the preferred methods for obtaining estimates of usual nutrient intake (Block 1989, Van Staveren *et al.* 1985). If researchers are only interested in a list of items that are typical of an individual's diet

rather than a specific list of items eaten during a certain period of time, the diet history seems more adequate to determine the typical diet. Most people are able to report what they typically eat, even if they cannot report exactly what they ate during a specific period of time.

This method also has some limitations. The data collection is a time-consuming process. The entire interview can take up to two hours to complete. Interviewers who use this method must be highly trained. Because of the large amount of information collected, the data is very difficult to analyze. In addition, the method also requires a cooperative respondent with the ability to recall his or her usual diet.

Next step: analyzing nutrient and energy content

Once information on food intake has been obtained, the next step is to determine nutrient and energy content, so that results can be compared to the dietary recommendations. To get a general picture of dietary intake, an individual's food record can be compared with a guide for diet planning, such as the MyPyramid. For example, does the individual consume the recommended number of servings of milk per day? A more precise and detailed analysis of dietary intake may be done by determining the nutrient content of each food item. Information concerning the nutrient content of foods may be found on food labels, in published food composition tables, and in computer databases. Food labels provide information only for some nutrients, and they are not always available, especially for raw foods such as fruits, vegetables, fish, meats, and poultry. Food composition tables, however, contain information that is much more comprehensive. They typically provide values for energy and nutrients, including protein, carbohydrates, fat, vitamins, and minerals and for other important food components such as fiber. Data regarding food composition are usually made public and may be found on the government websites of most countries.

Using food composition tables can be time-consuming and tedious. Such a shortcoming may be overcome by using computer programs and their associated nutrient databases that are readily available for professionals and for home use. To analyze nutrient intake using a computer program, one must enter each food and the exact quantity consumed into the program (Appendix G). If a food is not found in the database, an appropriate substitute may be used or the food may be broken down into its individual ingredients. For example, homemade vegetable soup could be entered as generic vegetable soup, or as vegetable broth, carrots, green beans, rice, and so on. If a new product has come on the market, the information from the food label may be added to the database. The program can calculate nutrient intake for each day or average them over several days. It can also compare nutrient intake to recommended amounts.

Computer analysis has several limitations. It is not available to everyone, and may be prohibitive due to the lack of computer equipment and/or the cost. Most computer programs have a limited number of foods in the database, which may cause a problem when a certain degree of accuracy is needed. However, this may be overcome by choosing a good program and having a good knowledge of foods, so that adequate substitutions may be made.

Other methods of assessing nutritional health

The other components of nutritional assessment include anthropometric measurements, laboratory measurements, and clinical assessments. Each of these assessment methods provides a unique perspective of an individual's nutritional status.

Height, weight, and body size

Anthropometric measurement assesses physical dimensions and body composition. Common examples of anthropometric measurements include health, weight, and body size. These measurements can be compared with population standards or used to monitor changes in an individual over time. If an individual's measurements differ significantly from standards, it could indicate health problems. For example, weight is often used to assess a person's risk for certain chronic diseases, such as heart disease and type 2 diabetes, because being overweight or obese can lead to many health problems, especially as he or she ages. Height and weight are also used to assess nutritional status in infants and children and are typically measured shortly after birth and throughout childhood. For example, children who are small for their age may have a nutritional deficiency, although this information should be evaluated only within the context of their personal and family history. Those who are smaller than the standard may simply have inherited their small body size or may be considered adequately nourished if they have never weighed more than their current weight and are otherwise healthy. Chapter 12 provides more details with regard to the assessment of body composition, i.e., percentage of body fat.

Clinical assessments

Nutritional status can be evaluated using a clinical assessment. During this procedure, the clinician or researcher takes a medical history to obtain information about previous disease, weight loss and/or gain, surgeries, medications, and other relevant information such as family history. Specifically, the health care provider asks the patient whether he or she has been experiencing any unusual symptoms such as lack of energy, blurred vision, or loss of appetite. Because these symptoms are not observable by others and can only be reported by the patient, symptoms are often overlooked.

The medical history is typically followed by a physical examination to determine whether there are visible signs of a health problem. In a physical examination, all areas of the body including the mouth, skin, hair, eyes, and fingernails are examined for indications of poor nutrition status. **Signs** of illness are different from **symptoms**, because signs can be seen by others, whereas symptoms are what the patient experiences, which may be more subjective. Some signs may indicate poor nutritional status, such as skin rashes, swollen ankles or edema, or bleeding gums. Physical examinations almost always include anthropometric measurements such as height and weight. Determining whether the signs or symptoms noted in a physical examination are due to malnutrition requires that they be evaluated in conjunction with the results of laboratory measurements and within the context of each individual's medical history.

Clinical assessment has its advantages; for example, it is the only way that health care providers can ask questions concerning symptoms of malnutrition. Furthermore, signs of some extreme forms of malnutrition are very distinct, and observation of them can make clinical diagnosis of a particular nutrient deficiency or toxicity relatively accurate. However, because signs and symptoms of many nutrient deficiencies are not apparent until they become severe, clinical assessment may not be adequate when malnutrition is more moderate in nature.

Laboratory measurements

Measures of nutrients or their metabolic by-products in the body such as blood and urine may be used to detect nutrient deficiencies or toxicities when compared with standard reference values (Table 13.2). They require laboratory analysis of biological samples taken

from blood or urine. In some cases, the sample is analyzed for a specific nutrient. Blood concentrations of calcium and vitamin D are often measured to assess the risk for osteoporosis especially in women who are approaching the menopause. To assess whether the body maintains its muscle mass, one can determine urinary concentration of **creatinine**, a by-product of skeletal muscle catabolism. Because blood carries newly absorbed nutrients to the cells of the body, the amounts of some nutrients in the blood may reflect the amounts in the current diet rather than the total body status of the nutrient. In this case, it may be necessary to analyze the cells in the blood or other tissues for indications of abnormal function such as altered rates of chemical reactions. For example, vitamin B6 is needed for chemical reactions involved in amino acid metabolism. When vitamin B6 is deficient, the rate of these reactions will be slower than normal.

Table 13.2 Normal blood values or reference range of nutritional relevance

Test variable	*Value/reference range*
Acidity (pH)	7.35–7.45
Alcohol	0 mg/dL
Ammonia	15–50 μg of nitrogen/dL
Bicarbonate	18–23 mEq/L (carbon dioxide content)
Blood volume	8.5–9.1% of total body weight
Calcium	8.2–10.6 mg/dL
Carotene	48–200 μg/L
Chloride	100–108 mEq/L
Copper	70–150 μg/dL
Creatinine	0.6–1.2 mg/dL
Folate	2–20 ng/ml
Glucose (fasting)	70–110 mg/dL
Hematocrit	Men: 45–55%; women: 37–48%
Hemoglobin	Men: 14–18 g/dL; women: 12–16 g/dL
Iron	Men: 75–175 μg/dL; women: 65–165 μg/dL
Lactate (lactic acid)	Venous: 4.5–20 mg/dL; arterial: 4.5–14.4 mg/dL
Lipids	Cholesterol: <200 mg/dL LDL cholesterol: <130 mg/dL HDL cholesterol: ≥40 mg/dL Triglycerides: <150 mg/dL
Magnesium	1.8–3.0 mEq/L
Oxygen partial pressure	83–100 mmHg
Oxygen saturation (arterial)	96–100%
Phosphorous	3.5–5.4 mg/dL
Platelet	150,000–350,000/mL
Potassium	3.5–5.0 mEq/L
Proteins	Total: 6.0–8.4 g/dL Albumin: 3.0–4.0 g/dL Globulin: 2.3–3.5 g/dL
Red blood cells	Men: 4.6–6.2 million/mm^3; women: 4.2–5.2 million/mm^3
Sodium	135–145 mEq/L
Urea nitrogen (BUN)	7–18 mg/dL
Vitamin A	30–70 μg/dL
Vitamin B_6	5–50 μg/L
Vitamin B_{12}	200–800 pg/dL
Vitamin C	0.6–2.0 mg/dL
Vitamin D (25-hydroxyvitamin D)	20–100 ng/mL
White blood cells	4500–10,000/mm^3
Zinc	0.75–1.4 μg/ml

There are advantages and disadvantages of using laboratory measurements. On the positive side, laboratory measurements can help diagnose a specific nutrient deficiency or detect a potential health problem, whereas other methods of nutritional analysis cannot. Laboratory data have been heavily used to evaluate risk for nutrition-related chronic diseases. For example, risks for cardiovascular diseases may be assessed by measuring levels of cholesterol in the blood. Measuring the amount of glucose in the blood may be used to diagnose diabetes. However, collecting and analyzing biological samples require technical expertise and are considered costly procedures. In addition, many factors such as time of day, age, sex, activity patterns, and use of certain drugs can influence the level of nutrients or their biomarkers in blood or urine. These extraneous factors must be taken into consideration when interpreting results of laboratory measurements.

Assessing energy expenditure and substrate utilization

Interest in monitoring energy expenditure and respiratory gas exchange during physical activity can be traced back almost 100 years ago when Haldane and Douglas, in preparation for the 1911 Anglo-American expedition to Pike's Peak in Colorado, developed the "Douglas bag" method that measures oxygen consumption and carbon dioxide production. Since then a wide range of electronic and computer-assisted metabolic systems have been developed, which allow a precise quantification of energy expenditure during various physical activities. In today's world where physical inactivity often plays a contributing role in the development of many chronic diseases, such technological advancement has enabled us not only to simply quantify the energy cost of an activity, but also to assess the association between physical activity and health and the effectiveness of interventions aimed at increasing physical activity in order to treat or prevent diseases.

Laboratory approaches

In general, in the laboratory setting there are two techniques employed in the measurement of energy expenditure and substrate utilization: (1) direct calorimetry, and (2) indirect calorimetry.

Direct calorimetry

Energy metabolism may be defined as the rate of heat production. This definition recognizes the fact that, when the body uses energy to do work, heat is liberated. This production of heat occurs through cellular respiration and mechanical work. **Direct calorimetry** involves the measurement of heat produced during metabolism. This technique works in a similar manner to the bomb calorimeter mentioned in Chapter 8, except it is large enough to allow an individual to live and work for a certain period of time (Figure 13.3). Energy expenditure during muscular exercise can be measured by installing an exercise device such as a treadmill, bicycle ergometer, etc. in the chamber. In this insulated calorimeter, a thin copper sheet lines the interior wall to which heat exchangers are attached. A known amount of water circulates through the heat exchanger regularly absorbing the heat radiated from the subject in the chamber, which reflects the metabolic rate of that person. Insulation protects the entire chamber so that any change in water temperature relates directly to the individual's energy metabolism. The air is recirculated, and carbon dioxide and water are filtered out of the air before it re-enters the chamber, together with added oxygen. The direct measurement of heat production in humans is proven to be very precise based on the well-defined concept that 1 calorie is equivalent to the amount of heat needed to raise 1 gram of water by 1°C. However, its application is limited because the

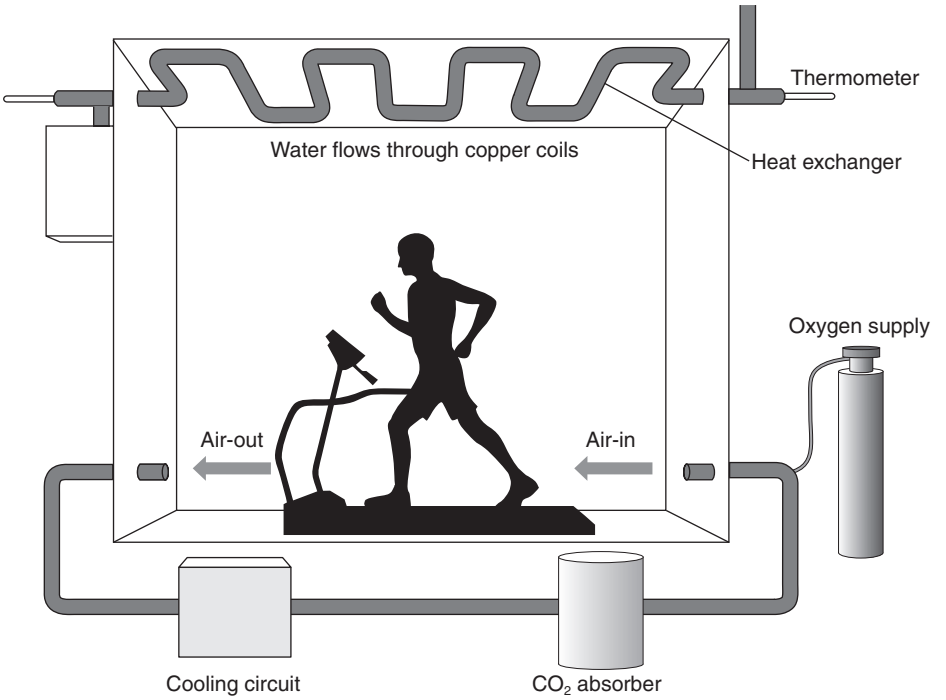


Figure 13.3 Direct calorimetry chamber

Source: Jeukendrup and Gleeson (2010). Used with permission.

technique requires considerable time, expense, and engineering expertise in operating and maintaining the equipment. In addition, though to a much lesser extent, the results of this technique could be affected in that not all the heat produced is liberated into the environment that can be captured and there will be extra heat produced due to the operation of the exercise equipment itself which does not result from metabolism.

Indirect calorimetry

Indirect calorimetry is the method by which measurement of whole-body respiratory gas exchange is used to estimate the amount of energy produced through the oxidative process. The rationale behind indirect calorimetry is that virtually all bioenergetic processes are oxygen dependent (Ravussin and Rising 1992). Indirect calorimetry differs from direct calorimetry in that it determines how much oxygen is required for biological combustion to be completed, whereas the latter measures directly the heat that is produced as a result of metabolism. The principle of indirect calorimetry may be explained by the following relationship:

$$\text{Substrate} + O_2 \longleftrightarrow \text{Heat} + CO_2 + H_2O$$

In light of this direct relationship between oxygen consumption and the amount of heat produced, it makes sense that measuring the amount of oxygen consumed can be a logical replacement for measuring the heat produced as a result of biological oxidation.

In order to convert the amount of oxygen consumed into heat equivalents, it is necessary to know the type of energy substrates that are metabolized, i.e., carbohydrate and fat. The energy liberated when fat is the only substrate being oxidized is 19.7 kJ or 4.7 kcal per liter of oxygen used. However, the energy released when carbohydrate is the only fuel being oxidized is 21.1 kJ or 5.05 kcal per liter of oxygen used. Although less accurate, energy expenditure of exercise is often estimated by using 5 kcal or 21 kJ per liter of oxygen used. Therefore, a person exercising at oxygen consumption of 2.0 liters min^{-1} would expend approximately 42 kJ or 10 kcal of energy per minute. Despite being simplistic, this assumed value of energy equivalency should be used with caution because it implies that over 95 percent of the energy comes from oxidation of carbohydrate. In reality this may not always be the case, as the level of carbohydrate oxidation should be much lower when exercise is performed at low intensities. Consequently, it has been suggested to use an energy equivalent of 4.825 kcal per liter of oxygen for occasions such as resting or low-intensity, steady-state exercises such as walking.

With indirect calorimetry, subjects are required to inhale ambient air with a constant composition of 20.93 percent oxygen, 0.03 percent carbon dioxide, and 79.04 percent nitrogen. Volume of O_2 consumed or VO_2 is determined from the change in volume of oxygen inspired compared with the volume of oxygen expired shown as follows:

$$\text{Volume of } O_2 \text{ consumed} = \text{volume of } O_2 \text{ inspired} - \text{volume of } O_2 \text{ expired}$$

The laboratory equipment used to measure oxygen consumption is illustrated in Figure 13.4. The volume of air inspired and expired is measured with a gas meter which is attached to a subject through a flexible hose and a face-fitting mask. The expired gas from the subject is analyzed for the fractions of oxygen and carbon dioxide by electronic gas analyzers. Results are then sent to a computer that is programmed to perform the necessary calculations of VO_2 and other metabolic parameters.

Figure 13.4 An open-circuit indirect calorimetry system

Source: Medical Graphics Corporation.

The technology of indirect calorimetry has become increasingly sophisticated during recent years. A room-sized chamber has now been made available based on the principle of open-circuit indirect calorimetry. Such a chamber appears similar to the chamber used as direct calorimetry but without the coils to measure heat exchange. It has all the basic furniture and utilities necessary to carry out various daily functions so that measurements can be made in a real-life situation. The chamber is equipped with the instrumentations that can measure oxygen uptake and carbon dioxide, as well as pulmonary ventilation, and these measurements can be performed continuously for an extended period of time. By using this large chamber, all components of daily energy expenditure may be assessed. They include basal metabolic rate (BMR), sleeping metabolism, energy cost of arousal (basal metabolic rate minus sleeping metabolism), thermal effect of meals, and the energy cost of physical activities.

Although indirect calorimetry does not involve the direct measurement of heat production, this technique is still considered relatively accurate in reflecting energy metabolism and substrate oxidation. In fact, this technique has been extensively used as a criterion measure in validation studies aimed at developing a new field-based method for quantifying energy expenditure. Compared to direct calorimetry, this indirect approach is relatively simpler to operate and less expensive to maintain and staff. With the recent emergence of portable versions, this technique may also be used under many free-living conditions such as common household and garden tasks and leisure physical activities.

Measurement of substrate oxidation

In addition to quantifying energy expenditure, indirect calorimetry provides a means of estimating the composition of fuels oxidized. This is accomplished by determining the ratio of volume of CO_2 produced to volume of O_2 consumed, which is referred as the **respiratory quotient** (RQ). Due to structural differences in the composition of carbohydrates, lipids, and proteins, complete oxidation of each nutrient requires different amounts of oxygen and produces different amounts of carbon dioxide. For example, the oxidation of 1 gram of glucose requires 0.746 L oxygen and produces 0.743 L carbon dioxide, and as a result, RQ is close to 1. On the other hand, the oxidation of 1 gram of free fatty acid (palamitic acid) requires 2.009 L O_2 and produces 1.414 L CO_2, and, as a result, RQ is close to 0.7. Differences in RQ caused by carbohydrate and fat oxidation are also illustrated in the following oxidative chemical reactions:

$$\text{Glucose } C_6H_{12}O_6 + 6O_2 \longrightarrow 6\ CO_2 + 6\ H_2O \qquad RQ = 6CO_2 \div 6O_2 = 1$$

$$\text{Palmitic acid } C_{16}H_{32}O2 + 23O_2 \longrightarrow 16\ CO_2 + 16\ H_2O \qquad RQ = 16CO_2 \div 23O_2 = 0.7$$

RQ serves as a convenient measure to provide quantitative information on the relative contributions of energy nutrients to the total energy provision at rest and during steady-state exercise. If RQ is found to be equal to 1, then all energy is derived from oxidation of carbohydrate energy substrates. If RQ is found to be equal to 0.7, then all energy is derived from oxidation of fat energy substrates. It is, however, very unlikely that fat or carbohydrate would be the only fuel used in most circumstances. In fact, during rest and submaximal exercise, RQ is often found to be somewhere between 0.7 and 1.0. Table 13.3 lists a range of RQ values and corresponding percentages of energy derived from fat or carbohydrate oxidation, which was first published by American nutrition scientist Graham Lusk (1924). This table also illustrates the **caloric equivalent of oxygen** corresponding to each RQ value. The caloric equivalent of oxygen is defined as the number of calories produced for each liter of oxygen used, and as shown in Table 13.3 this parameter is subject to the change in composition of carbohydrate and fat oxidation.

Table 13.3 Thermal equivalents of oxygen for the non-protein respiratory quotient (RQ) and percentages of calories derived from carbohydrate and fat

Non-protein RQ	*Kcal per LO_2*	*% carbohydrate*	*% fat*
0.70	4.686	0.0	100.0
0.71	4.690	1.1	98.9
0.72	4.702	4.8	95.2
0.73	4.714	8.4	91.6
0.74	4.727	12.0	88.0
0.75	4.739	15.6	84.4
0.76	4.750	19.2	80.8
0.77	4.764	22.8	77.2
0.78	4.776	26.3	73.7
0.79	4.788	29.9	70.1
0.80	4.801	33.4	66.6
0.81	4.813	36.9	63.1
0.82	4.825	40.3	59.7
0.83	4.838	43.8	56.2
0.84	4.850	47.2	52.8
0.85	4.862	50.7	49.3
0.86	4.875	54.1	45.9
0.87	4.887	57.5	42.5
0.88	4.889	60.8	39.2
0.89	4.911	64.2	35.8
0.90	4.924	67.5	32.5
0.91	4.936	70.8	29.2
0.92	4.948	74.1	25.9
0.93	4.961	77.4	22.6
0.94	4.973	80.7	19.3
0.95	4.985	84.0	16.0
0.96	4.998	87.2	12.8
0.97	5.010	90.4	9.6
0.98	5.022	93.6	6.4
0.99	5.035	96.8	3.2
1.00	5.047	100.0	0.0

The number of calories produced from one liter of oxygen used is less when fat is burned (i.e., 4.69 kcal/liter O_2) as compared to carbohydrate (i.e., 5.05 kcal/liter O_2). In order to determine energy expenditure accurately, we need to know not only the level of oxygen uptake, but also the composition of energy fuels being utilized.

RQ represents gas exchange across the blood–cell barrier within an organ or tissue bed. Thus, direct measurement of this parameter can be difficult because it requires an invasive medical procedure. However, this methodological limitation is overcome by determining VO_2 and VCO_2 at the lungs using indirect calorimetry. To recognize the fact that VO_2 and VCO_2 were measured at the lungs, the **respiratory exchange ratio** (RER) is used instead of RQ. RQ and RER depict the same ratio, but RER may be interpreted as the ratio of VCO_2/VO_2 corresponding to metabolism of the overall body rather than a specific tissue bed, and is typically determined using indirect calorimetry.

Caution should be used in situations where one measures RER, but uses the RQ table for quantifying substrate utilization. First, the RQ table was developed based on the assumption that the amount of protein oxidized is small and negligible, or it can be corrected for the oxidation of protein computed from nitrogen excretion in urine and sweat (Ferrannini 1988, Frayn 1983). Second, application of RQ assumes that oxygen and carbon dioxide

exchange measured at the lungs reflects the actual gas exchange from macronutrient metabolism within tissues. In this regard, exercise intensity could be of concern. It has been found that this assumption works well during exercise of light to moderate intensity. During heavy exercise, however, VCO_2 measured at the lungs represents not only those produced during energy metabolism, but also those derived from buffering of metabolic acid, which increases at a greater rate during high-intensity exercise. Consequently, the use of RER would no longer be accurate in reflecting the pattern of substrate utilization. Finally, the use of RER may not be adequate for those with pulmonary disorders as well because the pattern of gas exchange at the lungs may be altered due to obstructive ventilation.

Field-based techniques

The traditional chamber and calorimetry technology may be inadequate for reasons such as cost, instrumentations, and time necessary in running the test. It is also very difficult to use these sophisticated approaches to capture the complexity of activities in which people are engaged as they go about their daily lives. Consequently, there have been many attempts to develop relatively simple and more convenient methods to allow energy demands associated with free-living activities to be determined. Of those methods, the doubly labeled water technique, motion sensors, heart rate monitoring, and physical activity questionnaires or logs are perhaps the most common attempts for which their validity and reliability have been highly investigated. These field-based approaches enable us to track our physical activity participation in many free-living conditions. Although field-based techniques provide a convenient approach to the measurement of energy expenditure, they generally do not measure or distinguish metabolism of energy substrates such as carbohydrate and fat.

Doubly labeled water technique

The use of **doubly labeled water** for assessing energy expenditure in humans was first reported by Schoeller and Santen (1982). This technique requires the subject to consume a quantity of water containing a known concentration of the stable isotopes of hydrogen (^2H or deuterium) and oxygen (^{18}O or oxygen-18). The term **isotope** means one of two or more species of the same chemical element that have different atomic weights (Shier *et al.* 1999). Isotopes have nuclei with the same number of protons but varying numbers of neutrons. Stable isotopes denote those whose nuclei will not emit radiation and thus are not radioactive. Both ^2H and ^{18}O are used as tracers, as they are slightly heavier and can be measured within various body compartments. For example, through oxidative metabolism, labeled hydrogen is lost as ^2H_2O in sweat, urine, and water vapor during respiration, while labeled oxygen leaves as $H_2{}^{18}O$ in water and $C^{18}O_2$ in expired air. A mass spectrometer is then used to determine the difference in excretion rate between the two tracers and such difference then represents the rate of carbon dioxide production. Oxygen uptake is further estimated from VCO_2 as well as RQ, which is often assumed to be 0.85 (Black *et al.* 1986).

The primary advantage of using this technique to measure total energy expenditure is that it does not interfere with everyday life and thus may be used in a variety of free-living settings. The fact that this technique is not constrained by time would allow an acquisition of the typical daily energy expenditure. To date, the technique has been used in circumstances such as bed rest and during prolonged activities like climbing Mount Everest, cycling the Tour de France, rowing and endurance running, and swimming (Hill and Davis 2002, Stroud *et al.* 1997, Mudambo *et al.* 1997). The potential drawbacks of this technique include the high cost of the ^{18}O and both the expense and

specialized expertise required for the analysis of the isotope concentrations in body fluids by a mass spectrometer. As measurement is often taken over a long period of time, no information is obtained about brief periods of peak energy expenditure.

Motion sensors

Motion sensors are mechanical and electronic devices that capture motion or **acceleration** of a limb or trunk, depending on where the device is attached to the body. There are several different types of motion sensors that range in cost and complexity from the pedometer to the triaxial accelerometer. The pedometer is a relatively simple device used primarily to measure walking distance. It may be clipped to a belt or worn on the wrist and ankle (Figure 13.5). **Pedometers** count the motion by responding to vertical acceleration. The early version of this instrument is merely mechanic in that it has a lever arm attached to a gear, which rotates each time the lever arm clicks. The horizontal spring-suspended lever arm moves vertically up and down as a result of each step being made. More sophisticated pedometers are now commercially available. They rely on the use of a micro-electromechanical system (MEMS) comprised of inertia sensors and computer software to detect steps. These pedometers are battery operated and have digital readouts that can display not only the total steps and distance, but also values in calories. Some of them can be adjusted for stride length so that walking distance may be more precisely calculated.

Pedometers are generally small, low in cost, and may be used in epidemiological studies that deal with a large-scale population (Table 13.4). However, this wearable device has a number of limitations when used as a research tool. It is unable to distinguish vertical accelerations above a certain threshold, and thus cannot discriminate walking from running or different levels of exercise intensity (Bassett 2000). In terms of converting steps into energy expenditure, this device works on the assumption that a person expends a constant amount of energy per step. In Yamax pedometers, for example, this constant is assumed to be 0.55 cal/kg/step regardless how fast the person is moving (Hatano 1993). It is also important to note that for activities that do not involve locomotion, such as cycling or upper-body exercise, the unit may need to be attached to the body part that is moving.

Figure 13.5 Examples of digital pedometers

Table 13.4 Advantages and disadvantages of various objective field methods for assessing physical activity and energy expenditure

Method	*Advantages*	*Disadvantages*
Pedometers	• Small in size • Low cost • Suitable for epidemiological	• Unable to detect acceleration • Unable to quantify intensity, duration, and frequency • Unable to detect certain movements such as weight-lifting, cycling, and up-body exercise
Accelerometers	• Small in size • Detect the rate of movement or acceleration • Able to provide information on intensity, duration, and frequency	• Questionable in converting motion data into energy expenditure • Unable to detect certain movements such as weight-lifting, cycling, and up-body exercise • Unable to discriminate walking/running performed on soft or graded terrain
HR monitors	• Correlate closely with VO_2 • Measure all movements including those that cannot be detected by motion sensors • Able to provide information on intensity, duration, and frequency	• Weak relation with VO_2 in low-intensity domain • Require individual calibration curves for accurate estimates of energy expenditure • HR subject to change in stress, body posture, dehydration, environmental temperature
Combining motion HR monitoring	• Overcome major weakness associated with motion sensors and HR monitors in addition to the advantages mentioned above	• Time-consuming in data analysis • Cost prohibitive • Necessary to validate the use of algorithm to estimate energy expenditure using large and heterogeneous samples and during various activities

It should also be noted that only a very small percentage of the population (~2 percent) own a wearable device, which limits its application in promoting physical activity. However, the movement sensor used for pedometers is now being installed in most smartphones loaded with activity or fitness apps. Considering that nearly two-thirds of adults in the United States own a smartphone, this technological advancement can have a profound effect in enhancing public awareness of physical activity. Just as wearable devices, these smartphones are also able to store data over a specific time period. A recent study has also found that smartphones are just as accurate as wristband pedometers in detecting steps and daily activity (Case *et al.* 2015).

Accelerometers are more sophisticated electronic devices that measure acceleration made by body movement. Unlike pedometers, accelerometers are able to detect the rate of movement or the intensity of exercise, as acceleration is directly proportional to muscular force being exerted. Accelerometers can also measure acceleration in one (uniaxial) or three (triaxial) planes. Although a variety of different models are now commercially available, the Caltrac™ and Computer Science Applications™ (CSA) are the two most commonly used uniaxial accelerometers, whereas the Tritrac R3D™ and Tracmor™ are the two more commonly used triaxial accelerometers (Ainslie *et al.* 2003). Structurally, the accelerometer is equipped with a transducer made of piezoceramic material with a brass center layer. When the body accelerates the transducer, which is mounted in a cantilever beam position, bends, producing an electrical charge that is proportional to the force being exerted by the subject. This creates an acceleration–deceleration wave and the area under this wave is summed and converted into digital signals referred to as "counts." Results can be displayed on a screen as an accumulated total or downloaded as raw data to be further analyzed. Most current models also have the ability to display the level of accumulated energy expenditure for an extended period of time. This is done through a microprocessor that utilizes an activity–energy conversion factor as well as prediction equations for BMR based on age, body size, and gender as independent variables (Washburn *et al.* 1989).

One most notable advantage of accelerometers is that they have the ability to detect the rate of movement and thus the intensity of exercise (Table 13.4). Together with the use of an internal clock, this intensity-discriminating feature will help characterize the intensity and duration of physical activity being performed. In doing so, a dose–response relationship of physical activity to health and fitness outcome may be assessed. Other advantages are that they are small in size, can be worn without interfering with normal movement, and record data for extended periods of time. The instrument also seems to be reliable. By having a subject wear two Caltrac™ devices on the left and right sides of the body, Sallis *et al.* (1990) observed that the inter-instrument reliability reached 0.96.

A number of studies have reported significant correlations between energy expenditure estimated by accelerometers and by other proven accurate methods, such as indirect calorimetry and the doubly labeled water technique. However, an equal amount of studies also found that this technique underestimated energy expenditure. The high validity for this instrument to be used for assessing physical activity appears to be demonstrated primarily in studies that employed level walking and running (Handelman *et al.* 2000). Questions still remain as to whether accelerometers are able to accurately assess energy expenditure during leisure activities such as household and occupational activities, weight-bearing and static exercises such as cycling and load carriage, and during walking/running that are performed on soft or graded terrain (Handelman *et al.* 2000, Sherman *et al.* 1998).

Given that a triaxial accelerometer combines three independent sensors to detect acceleration in the three-dimensional space, it seems logical that it would be more accurate in capturing physical activities than a single plane accelerometer. However,

validation results for supporting this contention are mixed. Welk and Corbin (1995) reported that both Caltrac™ (uniaxial) and Tritrac™ (triaxial) were similar in reflecting aspects of lifestyle activities. On the other hand, Bouten *et al.* (1996) and Eston *et al.* (1998) found that a three-dimensional monitor was better in predicting oxygen consumption during physical activities as compared to a uniaxial monitor. In light of advantages and concerns associated with the accelerometer, there is still a need to continue improving not only the hardware in order to better track the motion, but also the software so that converting activity counts into energy value can be made more accurately.

Heart rate monitoring

Due to the difficulties encountered in measuring VO_2 and thus energy expenditure in the field, a steady interest has been devoted to developing less direct methods of recording physiological responses associated with VO_2. Among those physiological parameters investigated are heart rate (HR), pulmonary ventilation, and body temperature. However, monitoring HR appears to be the most popular technique. During exercise, there is a fairly close and linear relationship between heart rate and VO_2 or energy expenditure during dynamic exercise involving large muscle groups; that is, the greater the HR, the greater the VO_2. This is especially the case when HR ranges from 110 to 150 beats·min^{-1} where the relationship between these two parameters is found to be linear. As such, it is reasonable to use HR as a physiological marker of VO_2 to assess physical activity and its associated energy expenditure. HR is relatively low cost, non-invasive, and easy to measure. With today's technology, HR can be monitored and recorded with the use of a chest strap transmitter and a small receiver watch. A typical HR monitor transmits the R-R waves of electromyography (ECG) into a receiver in which ECG signals may be digitized and displayed. Many advanced models are also equipped with an internal clock that allows sampling over different time intervals and has the ability to store data over a period of days or weeks, thereby providing information on various components of physical activity, including intensity, duration, and frequency.

With the HR monitoring technique, the key issue lies in the precision of converting HR into energy expenditure. This is because HR in relation to energy cost can be affected by many factors other than physical activity per se. Factors such as age, fitness, and resting metabolism may be accounted for by using individualized HR–VO_2 curves or by using measures of relative intensity (e.g., percentage of HR reserve) that adjust for age and fitness. However, there are still some doubts that are deserving of attention (Table 13.4). For example, a question remains as to whether HR is a valid indicator of energy expenditure during low-intensity activities due to its weak relationship with VO_2 within the low-intensity domain (Freedson and Miller 2000). This is a pertinent question in that the intensity at which many daily activities are performed range from low to moderate. HR is also more susceptible to emotional stress that would result in a disproportional rise in HR for a given VO_2. In addition, HR may vary due to changes in stroke volume, and this latter parameter is influenced by body posture, exercise modes, and heat stress and dehydration.

Combining HR and motion monitoring

Both accelerometry and HR monitoring are the field-based methods that have been commonly chosen for assessing physical activity and energy expenditure. However, as discussed earlier, there are limitations associated with each method when used alone. It appears that limitations of HR monitoring are primarily due to biological variance. For example, as mentioned earlier, the HR–VO_2 relation has been found to be affected by

age, gender, fitness, stroke volume, and psychological stress. Responses of HR can also be influenced by ambient temperature, hydration status, and quantity of muscle mass involved in the activity (Haskell *et al.* 1993, Brage *et al.* 2003). On the other hand, the limitations of accelerometry are mainly biomechanical in that the technique is generally unable to adequately detect increases in energy expenditure due to (1) movement up inclines, (2) an increase in resistance to movement, or (3) static exercise. In addition, a single sensor cannot identify movement that involves various parts of the body. As errors associated with the two methods are not inherently related, the combination of HR and accelerometry should in theory yield a more precise estimate of physical activity and energy expenditure as compared to either when used independently.

Over the past decade or so, some studies have been attempted to examine the validity of the simultaneous heart rate–motion sensor technique for measuring energy expenditure during exercise in the laboratory and in a field setting (Heskell *et al.* 1993, Luke *et al.* 1997, Rennie *et al.* 2000, Strath *et al.* 2001a, 2001b, Brage *et al.* 2003). In general, these studies have found that measuring both HR and movement concurrently is a better approach in estimating oxygen consumption and energy expenditure. In these studies, both HR and movement counts were recorded at the same time. VO_2 was estimated by using data on HR, motion, and both HR and motion. Each estimated VO_2 was then compared against criterion VO_2 measured with a standard technique, i.e., indirect calorimetry. As information on both HR and motion were available, these studies were able to use the motion data to exclude HR that was increased due to non-exercise reasons or use the HR data to capture an increase in energy metabolism that was not detected by motion sensors. Some studies recorded HR and motion using two or more devices or sensors attached to different body parts, which may be problematic in terms of this technique being used in a field setting for a long period of time. To date, a single unit that detects HR and motion with only one sensor has been developed for use in tracking physical activity (Figure 13.6). This device uses a sophisticated **algorithm** in determining energy expenditure and can record data for as long as 11 days.

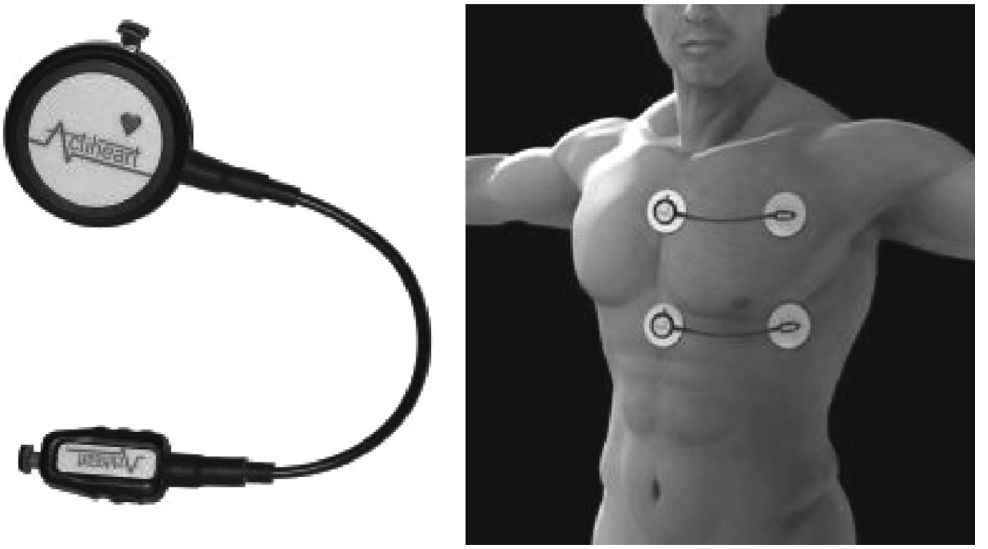


Figure 13.6 Illustration of Actiheart™ that combines HR and motion monitoring to track physical activity and energy expenditure

Apparently, this combined approach has many advantages. It overcomes the major weakness associated with HR monitoring and motion sensing alone (Table 13.4). For example, HR monitoring will not be subject to the error of movement sensing such as detecting the level of activity during resistance exercise, swimming, and cycling. Likewise, movement sensing complements HR monitoring, as it allows differentiation between increased HR caused by physical activity and that caused by other non-exercise-related influences. Nevertheless, this method still requires an individualized calibration curve to be established for both HR and movement counts, which could be time-consuming. Perhaps due to such technical difficulty in dealing with multiple sensing, most validation studies have used only a relatively homogeneous and small sample size. It is hopeful that future effort will be directed to examine whether this combined approach will be sufficiently precise to preclude the need for individual calibration. Currently, the validity of this technique remains equivocal. By using a low- to moderate-intensity domain, Spierer *et al.* (2011) found that the Actiheart monitor as shown in Figure 13.6 did not provide any better energy expenditure estimates than using HR monitoring alone. However, Barreira *et al.* (2009) revealed that this combined accelerometry/HR method was able to accurately measure physical activity under free-living conditions.

Multi-sensor monitoring system

More recently, a device called a SenseWare™ armband (SWA) was made available on the market to assess energy expenditure. This device is worn on the right upper arm over the triceps muscle and enables continuous physiological monitoring outside the laboratory (Figure 13.7). It has an ergonomic design that makes it easy to slip on and off and does not interfere with day-to-day activities or sleeping. In this device, there are multiple sensors that can measure various physiological and movement parameters simultaneously, including body surface temperature, skin vasodilatation, rate of heat dissipation, and two-axis accelerometer. Data from these parameters together with demographic information including gender, age, height, and weight are then used to estimate energy expenditure employing a generalized algorithm. The principal difference of this system compared to those discussed previously is the inclusion of a heat flux sensor. This will allow the system to detect a change in heat produced as a result of metabolism.

Figure 13.7 An example of a SenseWear™ armband

Two generations of SWA have been developed thus far. The newer version has an improved design and includes a replaceable AAA battery and a USB connector. However, the validity of this system remains to be substantiated. It appears that the system is accurate in tracking resting energy expenditure (Fruin and Walberg Rankin 2004, Malavolti *et al.* 2007). However, it remains questionable with regard to its ability to detect energy expenditure during exercise. In comparing SWA with indirect calorimetry, Fruin and Walberg (2004) and Vernillo *et al.* (2015) failed to demonstrate a good validity of SWA in estimating energy expenditure of flat, uphill, and downhill walking, although the device was found to be reasonably accurate for exercise performed on a cycle ergometer (Fruin and Walberg 2004). The use of SWA also seems problematic in tracking energy expenditure during intermittent exercise and recovery (Zanetti *et al.* 2014). Jakicic *et al.* (2004) also observed differences between SWA and indirect calorimetry during treadmill walking, cycling, stair stepping, and arm cranking. Interestingly, in this latter study, no difference was observed when the authors adopted a series of mode-specific algorithms. This finding is appealing in the sense that to use multiple algorithms would require the development of a mechanism that allows the device to switch between algorithms to be developed so that minimal burden can be placed upon the user.

Subjective measures

There is a range of subjective methods available for the assessment of energy expenditure in humans. These methods may be classified into categories of (1) questionnaires, and (2) activity log/diary. In general, questionnaires may be viewed as primarily recall-based and subjects are required to provide information about the pattern of their daily activities that have already occurred. Questionnaires have been used to assess physical activities for the previous 24 hours, the previous week, and the previous year. Some questionnaires have been structured to focus specifically on occupational or leisure-time activities. Other questionnaires have been quite general in searching out information on activities that have occurred both on and off the job. Questionnaires may be further divided into those that are self-reported and those that are interviewer-administered.

Activity logs or diaries involve logging subjects' activities periodically and this may be done in a frequency ranging from every minute to every few hours. This method often includes a standardized form used to facilitate both compliance and quality. Some forms require subjects to record activities minute by minute whereas others require subjects to record the change in activity. In these forms, names of activities are often abbreviated to make recording easier. In some activity logs, activities to be recorded could be specific enough to include not only the type, but also the intensity and duration. This method demands a greater level of attention from subjects in order to maintain their diary. To alleviate this burden on subjects, some researchers have used a wristwatch that alerts the subject to record activities at specified times.

Both questionnaires and activity logs/diaries have been frequently used in large population surveys and epidemiological studies. This is mainly because these techniques are relatively inexpensive as compared to HR or motion monitoring. With these techniques, specific activities may be identified together with information on intensity, duration, and frequency. In addition, data may be collected by many subjects simultaneously. However, there are some limitations to each of these methods. Quantifying various aspects of physical activity such as type, intensity, duration, and frequency, which are important in estimating energy expenditure, is difficult. For example, with questionnaires, subjects may not necessarily recall all activities they have performed and/or they may overestimate or underestimate the intensity and duration of certain activities. These shortcomings may particularly be the case when a questionnaire is administered to children who have lower cognitive

functioning (Janz *et al.* 1995). There is also evidence that physical activity was underestimated in women when household chores were not included in the surveys (Ainsworth and Leon 1991). With the activity log/diary technique, recording activities frequently over a long period of time could be difficult. This technique may also influence the pattern of activity of the subject who records his or her ongoing activities in that the subject may purposely modify his or her behaviors due to the survey.

Summary

- Using dietary analysis has allowed us to assess adequacy of dietary intakes of individuals and groups, to monitor trends in food and nutrient consumption, to study the relationship between diet and health, to establish food and nutrition regulations, and to evaluate the success and cost-effectiveness of nutrition and risk reduction programs.
- The 24-hour recall, food intake records, and food frequency questionnaires are the three commonly used methods for assessing one's dietary status. No single best method exists for measuring dietary intake. Each method has certain advantages and disadvantages. The method used depends on time constraints, subject characteristics, available resources, and whether the intent is to provide quantitative information or to merely estimate an individual's usual intake.
- The 24-hour recall method involves a registered dietician or a trained interviewer asking people to recall exactly what they ate during the preceding 24-hour period. This method is quickly administered, does not alter eating patterns, and has a low respondent burden. However, it does not provide data representative of an individual's usual intake.
- A food diary or food intake record can assess one's diet more accurately. Using this method, the respondent records, at the time of consumption, the identity and amounts of all foods and beverages consumed for a period of time, usually ranging from two to seven days and including at least one weekend day. This method does not rely on memory and can provide more detailed intake data, but requires a high degree of respondent cooperation and may result in alterations of diet.
- Food frequency questionnaires assess energy or nutrient intake by determining how many times a day, week, month, or year an individual consumes a limited checklist of foods that are major sources of nutrients or of a particular dietary component in question. This method provides data that is more representative of an individual's usual intake and is useful in revealing diet–disease relationships. However, it may not give an accurate estimate of quantity of foods consumed and respondents must be able to recall and describe their diets correctly.
- Being able to accurately determine energy expenditure of daily living including physical activity is critical for several reasons: (1) to quantify the participation of physical activity; (2) to monitor compliance with physical activity guidelines; (3) to understand the dose–response relationship between physical activity and health, and (4) to assess the effectiveness of intervention programs designed to improve physical activity levels.
- There are two laboratory procedures commonly used to assess human energy expenditure: (1) direct calorimetry, and (2) indirect calorimetry. Direct calorimetry measures directly the heat produced as a result of metabolism, whereas indirect calorimetry measures the amount of oxygen being used during energy transformation.
- Respiratory quotient (RQ) that represents gas exchange across the blood–cell barrier within tissue beds is a key parameter used in determining the composition of substrate utilization. This is based on the fact that oxidizing carbohydrate and fat

requires different amounts of oxygen and produces different amounts of carbon dioxide. Under most circumstances, this parameter may be estimated by measuring gas exchange occurring at the lungs and the ratio of VCO_2/VO_2 obtained is referred to as respiratory exchange ratio (RER).

- Pedometer, accelerometer, and heart rate monitoring are the three most commonly chosen techniques for assessing physical activity and energy expenditure. However, there are limitations associated with each method. The errors associated with the pedometer and accelerometer appear to be mechanical in that both techniques are generally unable to detect increases in energy expenditure due to (1) movement up inclines, (2) an increase in resistance to movement, or (3) static exercise. On the other hand, limitations of HR monitoring are primarily biological. For example, the HR–VO_2 relation has been found to be affected by age, gender, fitness, stroke volume, psychological stress, and environmental temperature.
- Because errors associated with accelerometer and HR monitoring are not inherently related, a simultaneous heart rate/motion sensor technique has been developed. This combined approach has legitimate rationale, but is more expensive. Whether it is more accurate than any single-sensor device remains to be substantiated.
- Subjective measures of physical activity and energy expenditure are mainly accomplished by using (1) questionnaires, and (2) an activity log/diary. Questionnaires are often conducted in recall fashion and subjects are required to provide information on activities that have already occurred. Activity logs or diaries are carried out by an individual periodically as their day goes by. These subjective methods provide the least expensive approach to tracking physical activity and energy expenditure and this advantage can be important when carrying out studies that use large sample sizes.

Case study: using indirect calorimetry to optimize nutrition

Richard is on the college track team. His coach suggests that he participate in an off-season training program aimed to optimize his weight and body composition. He also needs to watch carefully what he eats in order to achieve a desirable energy balance. One of the major activities in the training program is 60-minute steady-state running at about 7 miles an hour, 3 times a week. Richard wonders how many calories he will burn from this activity and how many of the calories expended come from using fat. He also wants to know his resting metabolic rate in order to better plan his diet.

Richard was able to partake in a testing session in the Human Performance Laboratory at his college, where the lab technician used indirect calorimetry to determine his resting metabolic rate and energy utilization during running at 7 miles an hour. The following are the results of this test:

- Oxygen uptake (VO_2) at rest = 0.28 liters/minute
- Respiratory exchange ratio at rest = 0.75
- The average VO_2 during running = 1.8 liters/minute
- Respiratory exchange ratio during running = 0.90

Questions

- What is Richard's resting metabolic rate in (1) kcal/min, and (2) kcal/day?
- How many calories did Richard expend during 60 minutes of running?
- What is the primary fuel that Richard used (1) at rest, and (2) during running?
- How many calories of carbohydrate and fat did Richard burn during running?

(Hint: You will need to use Table 13.3 to solve these questions.)

Review questions

1 What is the 24-hour recall method? What are the advantages and disadvantages associated with this method?
2 Describe how the food intake record method should be carried out. How does this method differ from the 24-hour recall method?
3 Why are food frequency questionnaires considered qualitative? What are the advantages and disadvantages associated with this method of tracking one's dietary status? How can this method be made semi-quantitative?
4 Both clinical assessments and laboratory measurements are also used in an overall assessment of one's nutritional status. What are the advantages of having these additional tools incorporated?
5 How is the term calorie defined? What is the difference between direct and indirect calorimetry?
6 What is the caloric equivalent of oxygen? Why is the caloric equivalent of oxygen higher for burning carbohydrate than for burning fat?
7 What is a respiratory quotient? How is this parameter used to determine the pattern of substrate utilization? What are limitations of this parameter?
8 If someone walks on a treadmill and is consuming oxygen at 1.5 liters a minute and expiring carbon dioxide at 1.2 liters a minute, what is the total energy expenditure of this individual if this exercise lasts for 30 minutes? How much of the total comes from oxidizing carbohydrate and how much comes from fat oxidation?
9 Describe how pedometers and accelerometers work in tracking energy expenditure of daily living.
10 Explain the rationale for heart rate to be used as a measure of energy expenditure. In what circumstances may this measurement be inaccurate?
11 Provide some multi-sensor examples and explain the thought process behind these devices.
12 What are the advantages and disadvantages associated with subjective measures of physical activity using questionnaires or activity logs?

Suggested reading

1 Ferrannini E (1988) The theoretical basis of indirect calorimetry: a review. *Metabolism*, 37: 287–301.
Consult this paper to gain further understanding of how indirect calorimetry works. The paper reviews the theoretic basis of and the advantages and limitations associated with this laboratory technique.
2 Freedson PS, Miller K (2000) Objective monitoring of physical activity using motion sensors and heart rate. *Research Quarterly for Exercise and Sport*, 71: 21–29.
Motion sensors and heart rate monitors are the two objective methods of tracking one's physical activity level. This article provides a theoretical basis of these two field-based techniques and also discusses advantages and limitations associated with each method. The validity and feasibility of developing a technique that uses both of these methods simultaneously is also discussed.
3 Sallis JF, Saelens BE (2000) Assessment of physical activity by self-report: status, limitations, and future directions. *Research Quarterly for Exercise and Sport*, 71: 1–14.
Self-report instruments are the most widely used type of physical activity measure. In this review, the authors summarize findings on the validity and reliability of this method, identify its strengths and limitations, and discuss areas for further improvement.

4 Schutz Y, Weinsier RL, Hunter GR (2001) Assessment of free-living physical activity in humans: an overview of currently available and proposed new measures. *Obesity Research*, 9: 368–379.
This article is an excellent addition, which reviews not only the methods discussed in the textbook, but also some of the more newly developed measures and techniques, such as daytime physical activity level, activity-related time equivalent, daytime physical activity-level heart rate, as well as using the Global Positioning System Measures to track human motion.

Glossary

Acceleration the rate of change of velocity and expressed in meters/seconds^2.

Accelerometer a device that measures the acceleration of the person's center of gravity.

Algorithm a procedure or formula for solving a problem and often has steps that repeat or require decisions such as logic or comparison.

Caloric equivalent of oxygen amount of energy yielded from 1 liter of oxygen used.

Creatinine a breakdown product of creatine, which is an important part of muscle.

Dietary history a method of dietary analysis that assesses an individual's usual dietary intake over an extended period of time, usually a month to a year.

Direct calorimetry a laboratory procedure that directly measures the heat produced during metabolism.

Doubly labeled water water in which both the hydrogen and the oxygen are partly or completely labeled with an uncommon isotope of these elements for the purpose of tracing metabolic rate.

Food diary a method of dietary analysis that requires the person to record foods and beverages while consuming them.

Food frequency questionnaire a method of dietary analysis that assesses energy or nutrient intake by determining how frequently an individual consumes a limited checklist of foods that are major sources of nutrients or of a particular dietary component in question.

Indirect calorimetry a method by which measurement of whole-body respiratory gas exchange is used to estimate the amount of energy produced though the oxidative process.

Isotope any of the several different forms of an element each having different atomic mass.

Missing foods foods eaten but not reported in dietary analysis.

Pedometer a device, usually portable and electronic or electromechanical, that counts each step a person takes by detecting the motion of the person's hips.

Phantom foods foods not eaten but reported in dietary analysis.

Respiratory exchange ratio (RER) similar to respiratory quotient except that both oxygen consumption and carbon dioxide production are measured at the lungs rather than tissue beds.

Respiratory quotient (RQ) a ratio of oxygen consumption to carbon dioxide production, which is influenced by the use of carbohydrate and fat as energy fuels.

Signs objective evidence of disease and may be detected by others.

Symptoms subjective evidence of disease and often referred to as a feeling people other than the patient cannot see.

14 Body weight and composition for health and performance

Contents

Key terms

- Air displacement plethysmography
- Bioelectrical impedance analysis
- Body density
- Boyle's law
- Circumference
- Dual-energy X-ray absorptiometry
- Endomorph
- Hydrostatic weighing
- Obese
- Resistance exercise
- Storage fat
- Visceral fat
- Archimedes' principle
- Body composition
- Body mass index
- Cellulite
- Densitometry
- Ectomorph
- Essential fat
- Mesomorph
- Overweight
- Skinfold
- Subcutaneous fat

Height and weight measurements

One of the most important measurements in nutritional assessment is body weight or body mass. Body weight is an important variable in equations that predict energy expenditure and indices of body composition. Measurements of a person's weight in conjunction with his or her stature or height do lend some value in predicting health and risk of death. There is good evidence that overweight persons tend to die sooner than average-weight individuals, especially those who are overweight at a younger age (Must *et al.* 1999, National Task Force on the Prevention and Treatment of Obesity 2000). A positive relationship has been demonstrated between body mass index (BMI – a weight–height index discussed later in this chapter) and mortality rate for cancer, heart disease, and diabetes mellitus, when BMI is above 25 kg m^{-2}. Some researchers believe that the lowest mortality rates in the United States and many other Western nations are associated with body weights somewhat below the average weight of the population under consideration (National Task Force on the Prevention and Treatment of Obesity 2000). On the other hand, one should be cautioned against encouraging weight loss when it is not indicated. A body weight that is too low is unhealthy and increases risk of death. This may be seen in persons suffering starvation or anorexia nervosa. Existing evidence has suggested that as BMI falls below about 20, risk of death increases.

Weight–height tables

Body weight may be better assessed using weight–height tables. Weight–height tables are convenient, quick, and easy to use. They are designed to evaluate the extent of being overweight from sex and frame size, with the frame size being determining by measuring the width of the elbow. Weight and height can be easily measured, and most adults and many adolescent and children are able to understand and use the tables. The life insurance industry has been at the forefront of developing height–weight tables. The tables were developed by comparing the heights and weights of life insurance policy holders with statistical data on mortality rates and/or longevity of policy holders. The insurance industry has used the data from the tables to help screen applicants to avoid insuring persons who have high risks. Table 14.1 shows the 1983 Metropolitan Life weight–height table. This weight–height table has served as a benchmark based on the average ranges of body mass related to stature in which men and women aged 25 to 59 have the lowest mortality rate. Based on the data used for developing this table, it was found that the lowest mortality rates occurred among non-smokers weighing 80 to 89 percent of average weight (Manson *et al.* 1987). Therefore, the weights defined by the Metropolitan tables as recommended for a given stature were actually less than the average weights of the population under study.

Classifying subjects based on frame size is a common feature of the Metropolitan weight–height table. The frame size of an individual can be determined objectively, although this parameter has often been estimated based on subject self-appraisal. Several approaches to determining frame size have been developed, including biacromial breadth (distance between the tips of the biacromial processes at the tops of the shoulders) and bitrochanteric breadth (distance between the most lateral projections of the greater trochanter of the two femurs) (Katch *et al.* 1982), the ratio of stature to wrist circumference (Grant *et al.* 1981), and width of knee, wrist, and elbow (Frisancho and Flegel 1983). Measuring the width of the elbow appears to be the most common and practical way of determining frame size and was taken into the consideration when the 1983 Metropolitan weight–height table was developed. When measuring the width of the elbow, the subject should stand erect with the arm extended forward perpendicular to the body. The subject

Table 14.1 1983 gender-specific height–weight tables proposed by the Metropolitan Life Insurance Company

Height		*Small frame*		*Medium frame*		*Large frame*	
in	*cm*	*lb*	*kg*	*lb*	*kg*	*lb*	*kg*
Men							
62	157	128–134	58–61	131–141	60–64	138–150	63–68
63	160	130–136	59–62	133–143	60–65	140–153	64–70
64	163	132–138	60–63	135–145	61–66	142–156	65–71
65	165	134–140	61–64	137–148	62–67	144–160	65–73
66	168	136–142	62–65	139–151	63–69	146–164	66–75
67	170	138–145	63–66	142–154	65–70	149–168	68–76
68	173	140–148	64–67	145–157	66–71	152–172	69–78
69	175	142–151	65–68	148–160	67–73	155–176	70–80
70	178	144–154	66–69	151–163	69–74	158–176	72–80
71	180	146–157	67–70	154–166	70–75	161–184	73–84
72	183	149–160	68–71	157–170	71–77	164–188	75–85
73	185	152–164	69–72	160–174	73–79	168–192	76–87
74	188	155–172	70–73	164–178	75–81	172–197	78–90
75	191	158–172	71–74	167–182	76–83	176–202	80–92
76	193	162–176	72–75	171–187	78–85	181–207	82–94
Women							
58	147	102–111	46–50	109–121	50–55	118–131	54–60
59	150	103–113	47–51	111–123	50–56	120–134	55–61
60	152	104–115	47–52	113–126	51–57	122–137	55–62
61	155	106–118	48–54	115–126	52–57	125–140	57–64
62	157	108–121	49–55	118–132	54–60	128–143	58–65
63	160	111–124	50–56	121–135	55–61	131–147	60–67
64	163	114–127	52–58	124–138	56–63	135–151	61–69
65	165	117–130	53–59	127–141	58–64	137–155	62–70
66	168	120–133	55–60	130–144	59–65	140–159	64–72
67	170	123–136	56–62	133–147	60–67	143–163	65–74
68	173	126–139	57–63	136–150	62–68	146–167	66–76
69	175	129–142	59–65	139–153	63–70	149–170	68–77
70	178	132–145	60–66	142–156	65–71	152–173	69–79
71	180	135–148	61–67	145–159	66–72	155–176	70–80
72	183	138–151	63–69	148–162	67–74	158–179	72–81

Note
Adapted by including values in centimeters and kilograms. Weights obtained from men and women 25–49 years of age with indoor clothing weighing 5 and 3 lb, respectively.

then flexes the arm forming a 90-degree angle at the elbow, with the palm facing the subject. The person who measures places the heads of a sliding caliper at the points that represent the widest bony width of the elbow, and pressure should be firm enough to compress the soft tissue outside the bony structure. The measurement should be read at 0.1 cm or 1/8 in. Table 14.2 provides normative data allowing classification of frame size based on elbow breadth for men and women of different heights.

There are several considerations to bear in mind in using the 1983 weight–height table. The table is formulated based on insurance industry data, which are derived from people who were able to purchase non-group insurance and who were 25 to 59 years of age. These people were predominately white, middle-class adults. Therefore, African Americans, Asians, Native Americans, Hispanics, and low-income persons are not proportionally represented. The weight–height table was based on the lowest mortality,

Table 14.2 Elbow breadth classifications for males and females of various statures

Height		*Small frame*		*Medium frame*		*Large frame*	
in	*cm*	*in*	*mm*	*in*	*mm*	*in*	*mm*
Men							
61–62	155–158	<2 1/2	<64	2 1/2–2 7/8	64–73	>2 7/8	>73
63–66	159–168	<2 5/8	<67	2 5/8–2 7/8	67–73	>2 7/8	>73
67–70	169–178	<2 3/4	<70	2 3/4–3	70–76	>3	>76
71–74	179–188	<2 3/4	<70	2 3/4–3 1/8	70–80	>3 1/8	>79
≥75	≥189	<2 7/8	<73	2 7/8–3 1/4	73–83	>3 1/4	>83
Women							
57–58	145–148	<2 1/4	<57	2 1/74–2 1/2	57–64	>2 1/2	>64
59–62	149–158	<2 1/4	<57	2 1/4–2 1/2	57–64	>2 1/2	>64
63–66	159–168	<2 3/8	<60	2 3/8–2 5/8	60–67	>2 5/8	>67
67–70	169–178	<2 3/8	<60	2 3/8–2 5/8	60–67	>2 5/8	>67
≥71	≥179	<2 1/4	<64	2 1/2–2 3/4	64–70	>2 3/4	>70

and did not take into account the health problems often associated with obesity. These health problems include cardiovascular disease, cancer hypertension, hyperlipidemia, and insulin resistance, which are more prevalent among the obese. In addition, no special consideration was given to the status of cigarette smoking, which is associated with lower weight and a shorter life span. Including data on smokers in the table tends to make lower weights appear less healthy and higher weights healthier (Willett *et al.* 1991). Finally, the weight–height table does not differentiate between fat mass and fat-free mass. What really matters is the quality of the weight, not the quantity, and the "ideal weight" is not ideal for everyone at a given height. Many athletes weigh more than the average weight–height standards due simply to additional muscle mass. Being above the ideal weight based on the weight–height table should not necessarily dictate whether someone should lose weight.

Body mass index

Another measure of weight for a given height is the **body mass index** (BMI), also known as the Quetelet index. This index was an attempt by mathematician Lambert Adolphe Jacques Quetelet early in the nineteenth century to describe the relation between body weight and stature in humans. BMI is calculated in the metric system by dividing weight by the square of height, as shown below:

$$\text{BMI} = (\text{weight in kilograms}) \div (\text{height in meters})^2$$

An individual who is 1.75 m (or 5 ft, 9 in) and weighs 75 kg (165 lb) has a BMI of $75/(1.75)^2 = 24.49\,\text{kg/m}^2$. The normal range is between $18.5\,\text{kg/m}^2$ and $25.0\,\text{kg/m}^2$. Individuals with a BMI higher than $25\,\text{kg/m}^2$ are classified as **overweight** and individuals with a BMI higher than $30\,\text{kg/m}^2$ are classified as **obese**.

As reflected in the formula, the Quetelet index or BMI provides a height-free measure of obesity by adjusting body weight to height. In studies that involved a large sample size, a commonly used measure of obesity is the BMI. This is mainly because of its simplicity of measurement and calculation and its low cost. Studies have shown that the BMI correlates relatively well ($r \approx 0.70$) with the actual measurement of body fat from hydrostatic weighing. This index has also been found to correlate well with body composition

estimated from total body water, total body potassium, and skinfold technique. It is recommended by the National Institute of Health that physicians use the BMI in evaluating patients (National Task Force on the Prevention and Treatment of Obesity 2000). Many scientists also consider the BMI to be an appropriate way to assess body weight in children and adolescents (Dietz and Bellizzi 1999). For years, doctors have used height and weight measurements to assess a child's physical growth in relation to other children of the same age, and this is typically carried out by using the gender-specific BMI-for-age percentiles as shown in Figure 14.1. BMI may be used in conjunction with skinfold measurements or waist circumference as an improved means of assessing increased risk in adults for heart disease, stroke, type 2 diabetes, and premature death (National Institute of Health 1998). Table 14.3 shows classifications of overweight and obesity and associated disease risk based on BMI and waist circumference in adults.

The BMI may be a useful screening device for health problems. However, it reveals nothing about body composition and cannot distinguish between overweight resulting from obesity or from muscular development. Two individuals may have the same BMI but a completely different body composition. One could achieve his or her body weight with mainly muscle mass as a result of hard training, whereas the other could achieve his or her body weight by fat deposition as a result of a sedentary lifestyle. Without information about body composition, they may both be classified as obese. The possibility of misclassifying someone as overweight or obese by the BMI applied particularly to large-sized males, especially field athletes, body builders, weight-lifters, upper-weight class wrestlers, and American football players, such as linemen. It has been estimated that more than 50 percent of the National Football League were obese with a BMI greater than 30, yet the average percentage of body fat of linemen is about 18 percent. Thus, when assessing athletic populations, measuring body composition that includes fat mass and fat-free mass is more appropriate.

Body composition essentials

Body composition is defined as the ratio of fat to fat-free mass and is frequently expressed as a percentage of body fat (% body fat). The percentage of body fat is also regarded as relative fatness. Table 14.4 presents the recommended percentage of body fat standards for adults, middle aged, and elderly. The minimal averages and the

Table 14.3 Classification of obesity and overweight and disease risk associated with body mass index and waist circumference

Classification	*Obesity class*	*BMI (kg/m²)*	*Disease risk relative to normal weight and waist circumference**	
			Men ≤40 in Women ≤35 in	*Men 40 in. Women >35 in.*
Underweight		<18.5	–	–
Normal		18.5–24.9	–	–
Overweight		25.0–29.9	Increased	High
Obesity	I	30.0–34.9	High	Very high
	II	35.0–39.9	Very high	Very high
Extreme obesity	III	≥40	Extremely high	Extremely high

Source: adapted from National Heart, Lung, and Blood Institute (1998).

Note
* Diseases risk for type 2 diabetes, hypertension, and cardiovascular disease.

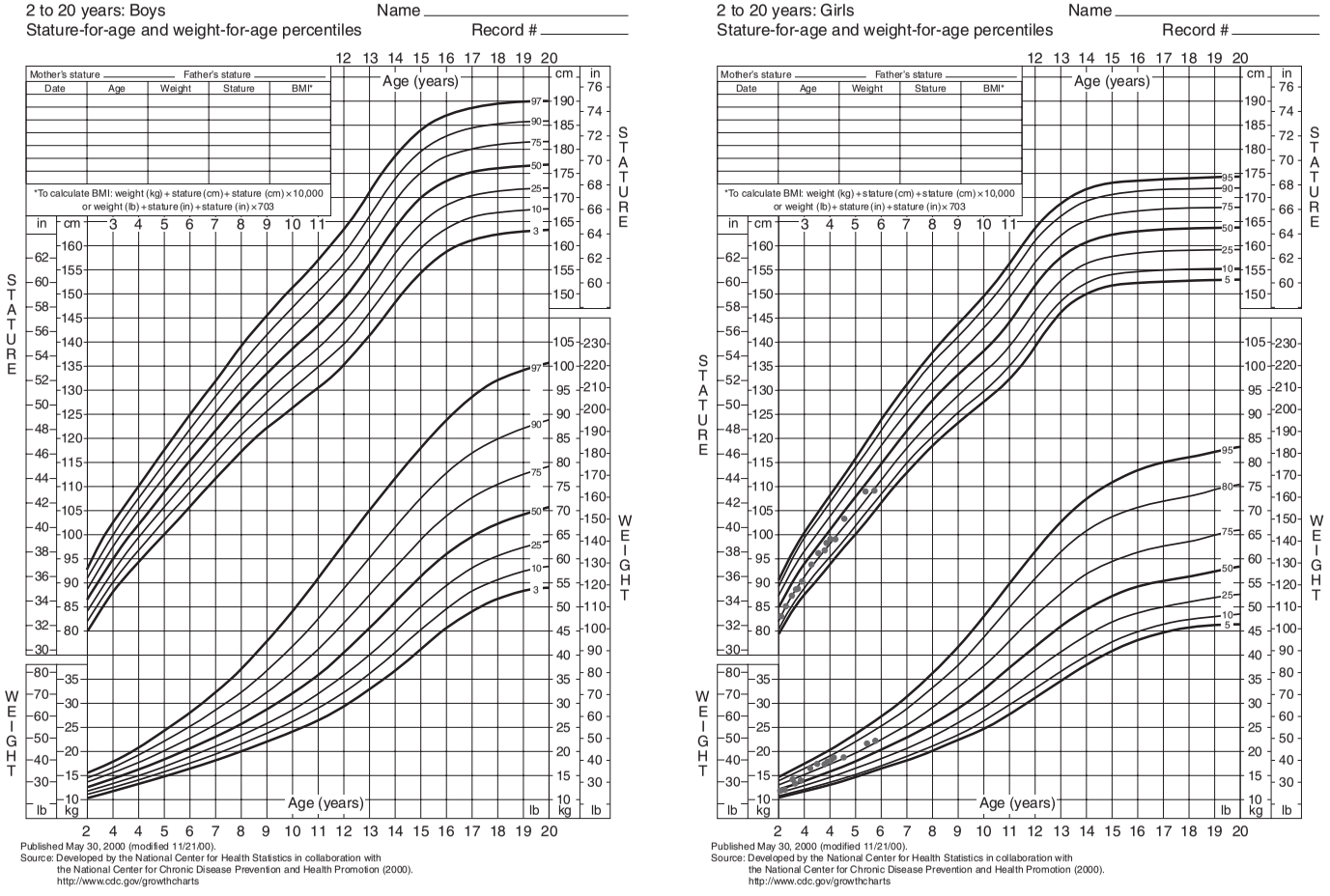


Figure 14.1 An example of the gender-specific BMI-for-age percentiles

Table 14.4 Percent body fat standards for healthy and physically active men and women

Populations	*Age (years)*	*Recommended % body fat levels*			
		Low	*Mid*	*Upper*	*Obesity*
Healthy males	18–34	8	13	22	>22
	35–55	10	18	25	>25
	55+	10	16	23	>23
Normal females	18–34	20	28	35	>35
	35–55	25	32	38	>38
	55+	25	30	35	>35
Physically active males	18–34	5	10	15	
	35–55	7	11	18	
	55+	9	12	18	
Physically active females	18–34	16	23	28	
	35–55	20	27	33	
	55+	20	27	33	

Source: adapted from Lohman *et al.* (1997).

threshold values for obesity vary with age and gender. For example, the average or median percentage of body fat values for adult men and women (18 to 34 years) are 13 percent for men and 28 percent for women, and standards for obesity are >22 percent for men and >35 percent for women.

Essential and storage fat

The total body fat consists of both essential fat and storage fat. **Essential fat** is stored in the bone marrow, heart, lungs, liver, spleen, kidneys, intestines, muscles, and lipid-rich tissues of the central nervous system. This fat is necessary for the efficient functioning of certain body structures such as the brain, nerve tissue, bone marrow, heart tissue, and cell membranes. The essential fat in adult males represents 3 to 5 percent of body weight. In females, essential fat includes additional sex-specific essential fat, which serves biologically important childbearing and other reductive functions. This additional sex-specific fat gives adult females approximately 12 to 15 percent essential fat. Essential fat is the level below which physical and physiological health would be negatively affected.

Storage fat is simply a depot for excess fat. The major fat depot consists of fat accumulation in adipose tissue. This fat is also referred to as energy reserve and contains about 83 percent of pure fat in addition to 2 percent protein and 15 percent water within its supporting structures. Average males and females have storage fat of approximately 12 and 15 percent of the body weight, respectively. Storage fat includes **visceral fat** that protects the various organs within the thoracic and abdominal cavities, but a much larger portion of the storage fat is found just beneath the skin's surface and is called **subcutaneous fat**. Subcutaneous fat accounts for over 50 percent of total body fat. When this type of fat is separated by connective tissue into small compartments that extrude into dermis, it gives a dimpled, quilt-like look to the skin and is known as cellulite. **Cellulite** is primarily fat, but may contain high concentrations of glycoproteins, particles that can attract water and possibly give cellulite skin a waffle-like appearance. Such skin change is much more common in women than in men.

The two-compartment body composition model

In order to make the most valid assessment of body composition, it is necessary to understand the underlying theoretical models used in the development of various body composition assessment techniques. Scientists have developed a variety of techniques to measure various body components including fat, protein, bone mineral, and body water. Of these components, fat remains of most interest due to its direct relationship with health and sports performance. Consequently, a more simplified, two-compartment model was developed (Brozek *et al.* 1963), which has been used as a theoretic basis for many of the body composition assessment techniques developed over the past several decades. In the two-compartment model, the body is divided into fat mass and fat-free mass, or, according to an alternative approach, into adipose tissue and lean body mass (Figure 14.2). An individual who has 20 percent body fat has 80 percent fat-free mass. It has long been considered that fat mass includes all the solvent-extractible lipids contained in body adipose and other tissues, and residual is the fat-free mass (Keys and Brozek 1953). Adipose tissue contains about 14 percent water, is nearly 100 percent free of electrolyte potassium, and is assumed to have a density of 0.9 g cm^{-3}. The fat-free mass is less homogeneous and is primarily composed of muscle, water, bone, and other tissues devoid of lipids. For example, solvent ether may be used to extract all the fat and lipids from minced animal carcass. That remaining after all the fat and lipids have been extracted would be the fat-free mass. The fat-free mass has a density of 1.1 g cm^{-3}, although this value may change depending on age, ethnicity, nutritional status, degree of fitness, and the body's state of hydration. The fat-free mass is also referred to as lean body mass. Lean body mass is similar to fat-free mass except that lean body mass includes a small amount of lipids that the body must have – for example, lipids that serve as a structural component of cell membranes or lipids contained in the nervous system. The essential lipid constitutes about 1.5 to 3 percent of lean body mass.

Computation of percentage body fat

Based on the cadaver analysis, which reveals that the density of body fat is 0.9 g cm^{-3} and the density of fat-free mass is 1.1 g cm^{-3}, two equations were developed to estimate

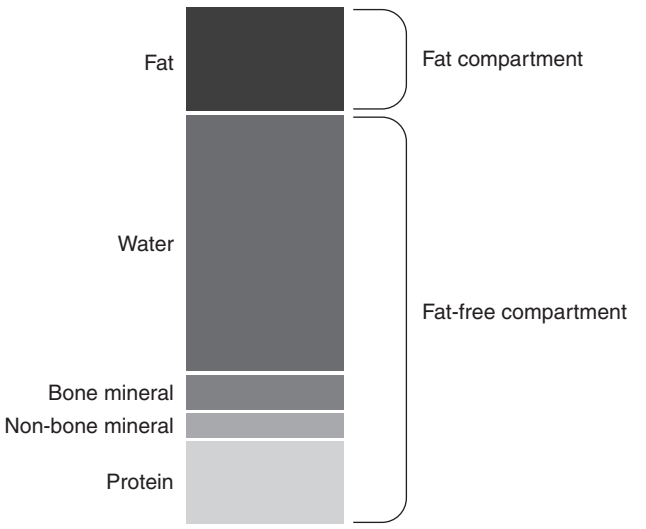


Figure 14.2 The two-compartment model for body composition

percentage body fat by incorporating the measured value of whole-body density (Brozek *et al.* 1963, Siri 1961):

$$\text{Siri equation: } \%\ \text{fat} = [(4.95/\text{body density}) - 4.50] \times 100$$

$$\text{Brozek equation: } \%\ \text{fat} = [(4.57/\text{body density}) - 4.412] \times 100$$

These formulas are based on the two-compartment model and yield similar % percentage body fat estimates for body densities ranging from 1.03 to 1.09 g cm^{-3}. For example, if an individual's measured whole-body density is 1.05 g cm^{-3}, the percentages of body fat, obtained by plugging this value into the Siri and Brozek equations, are 21.4 and 21.0 percent, respectively. In these formulas, body density is obtained from hydrostatic or underwater weighing, once considered the "gold standard" method. This method of measuring body composition is described in detail later in this chapter.

The generalized density values for fat (0.9 g cm^{-3}) and fat-free (1.1 g cm^{-3}) tissues represent averages for young and middle-aged adults. However, recent technological advances for measuring water (isotope dilution), minerals (dual-energy X-ray absorptiometry, DEXA), and protein (neutron activation analysis) have shown that the fat-free mass varies widely among population subgroups depending on age, sex, ethnicity, level of body fatness, training background, and hydration status. For example, a significantly larger average density of fat-free mass was found in Blacks (1.113 g cm^{-3}) and Hispanics (1.105 g cm^{-3}) than in Whites (1.100 g cm^{-3}) (Ortiz *et al.* 1992, Schutte *et al.* 1984, Stolarczyk *et al.* 1995). Consequently, using the existing equations established on the assumptions for Whites to calculate body composition from whole-body density of Blacks and Hispanics underestimates percentage body fat. Applying such constant density values for fat and fat-free tissues to growing children or aging adults also introduces errors in predicting body composition (Lohman and Going 1993). For example, the water and mineral content of fat-free mass continually increases during the growth period and decreases during the process of aging. This will reduce the density of the fat-free tissue of children and elderly below the assumed constant of 1.1 g cm^{-3}, thus overestimating percentage body fat. In addition, regular resistance training increases muscularity disproportionately to changes in bone mass, thereby reducing density of fat-free mass. Modlesky *et al.* (1996) found that the fat-free mass density of young white men with high musculoskeletal development due to regular resistance training was lower (1.089 g cm^{-3}) than the assumed value of 1.1 (g cm^{-3}), which caused an overestimation of percentage body fat by use of the Siri equation.

The three- and four-compartment body composition models

Most of the error associated with the two-compartment model lies not in the technical accuracy of the measurements but in the validity of previously outlined assumptions, which are based on analyses of several white male cadavers (Brozek *et al.* 1963, Siri 1961). To account for inter-individual variation in fat-free mass hydration, a three-compartment model was developed that includes fat mass, total body water, and fat-free dry mass. Water is the largest component of body mass and most of it is in lean tissues. It can be measured by an isotope dilution technique. Fat-free dry mass contains protein, glycogen, and minerals in bone and soft tissues. With the advancement in body composition technology such as dual-energy X-ray absorptiometry (DEXA), which yields values for bone mineral, a four-compartment model has emerged that includes fat mass, total body water, bone mineral, and residuals. This model is theoretically more valid than the three-compartment model because it controls for biological variation in both hydration and

bone mineral. However, it requires more measurements and is thus more costly and time-consuming. Table 14.5 summarizes the fat-free mass densities measured for different population subgroups using the three- or four-compartment model (Heyward and Stolarczyk 1996).

Body composition, health, and sports performance

How much should I weigh or how much body fat should I have? This is a complex question, and response depends on whether you are concerned primarily about your health, sports performance, or simply your physical appearance. The effect of body weight and fat on health has received considerable attention. Although being underweight may impair health, most of the focus has been on excess body weight and fat, particularly the relationship of obesity to health. For athletes, on the other hand, extra body weight may prove to be an advantage, especially in American football, rugby, ice hockey, heavyweight or sumo wrestling, and other sports in which body contact may occur or maintaining body stability is important. However, caution must be used because the effect of extra weight can be neutralized or proven ineffective if the athlete loses speed. As for physical appearance, everyone is the best judge of how he or she wishes to look. Nevertheless, a distorted image can lead to serious health problems or impairment in sports performance.

Body composition and health

Most of the attention to body composition and its influence on health has focused on the proportion of body fat. The percentage can vary from 3 to 5 percent of body weight in excessively lean individuals to as much as over 50 percent of body weight in morbidly obese individuals. By definition, obesity is simply an accumulation of fat in the adipose tissue. As shown in Table 14.4, for adult males, a level of body fat percentage above 25 is considered the low threshold for obesity, whereas adult females are considered obese when their body fat percentage exceeds 38 percent. Obesity is associated with various risk factors for chronic diseases, such as heart disease, hypertension, diabetes, some types of cancer, and osteoarthritis. Body fat can influence health in several ways; this is clearly demonstrated as body fat increases over time, and health conditions worsen in a parallel manner. However, when body fat levels fall too low, the resultant excessive leanness is potentially problematic as well.

Table 14.5 Selected population-specific fat-free mass density

Population	*Age (years)*	*Gender*	*Fat-free mass density*
White	20–80	Males	1.100
		Females	1.097
Black	18–32	Males	1.113
	24–79	Females	1.106
American Indian	18–60	Females	1.108
Hispanic	20–40	Females	1.105
Asian Natives	18–48	Males	1.099
		Females	1.111
Obese	17–62	Females	1.098
Anorexic	15–30	Females	1.087

Source: adapted from Heyward and Stolarczyk (1996).

Extremely low levels of body fat are associated with certain activities and sports. For example, some athletes, such as body builders or fitness competitors, may reduce their body fat percentages as a competition approaches or try to maintain lower levels of body fat throughout the year. Athletes participating in sports where body physique and leanness are important to success, such as gymnastics, figure skating, and diving, or sports involving weight classes, such as wrestling, weight-lifting, boxing, and lightweight rowing can become excessively lean during their competition seasons. Distance runners and cyclists also tend to have very low levels of body fat, usually as a result of the high-energy demands of their sports. As mentioned earlier, body fat percentages of approximately 3 to 5 percent for men and 12 to 15 percent for women have been considered the minimal level of adiposity necessary for maintaining health. Excessive leanness appears to affect female athletes more than their male counterparts. An extremely low body fat percentage has been considered a primary cause of reduced estrogen production and disruption of the menstrual cycle in some female athletes. It becomes more evident that the condition of amenorrhea may be more directly related to a chronic reduction in energy consumption. Often, an excessively lean body reflects conditions known as eating disorders and the Female Athlete Triad discussed in Chapter 10. These conditions, if left untreated, can have long-term health and psychological consequences.

Fat-free mass is an important component of body composition for health. Higher levels of fat-free mass can predict more desirable bone density and skeletal muscle mass. Bakker *et al.* (2003) revealed that compared with total body weight, standing height, BMI, waist circumference, waist-to-hip ratio, and skinfold thickness and fat mass, fat-free mass was the most important determinant of ten-year longitudinal development of lumbar bone mineral density in adult men and women. As the fat-free mass is largely composed of skeletal muscle tissues, such a relationship between fat-free mass and bone mineral can be explained by mechanical stresses mediated through gravitational action and muscle contractions on bone. Greater bone density is associated with greater bone integrity, which in turn reduces the risk of bone fracture as well as osteoporosis in the future. Likewise, having more skeletal muscle is associated with increased muscular strength and decreased risk of physical injury. As muscle is more active metabolically than adipose tissue, increased skeletal muscle mass may be related to increased daily energy expenditure, which can in turn reduce the possibility of weight gain and obesity. In addition, having more skeletal muscle can improve glucose tolerance and decrease the risk of diabetes mellitus. Indeed, skeletal muscle is one of the major target organs responsible for taking up glucose upon the action of insulin.

Recently, a great deal of attention has been focused on the benefits that resistance exercise can have in aiding glucose regulation in persons with type 2 diabetes. This is in part because **resistance exercise**, which is defined as the performance of dynamic or static muscular contractions against external resistance of varying intensities, is most effective in improving or maintaining skeletal muscle mass and function. A number of studies have shown improved insulin sensitivity and enhanced glucose clearance following programs of resistance training (Holten *et al.* 2004, Ferrara *et al.* 2006). Resistance training has also been shown to be effective in lowering blood pressure (Cornelissen and Fagard 2005). It is clear that regular conditioning involving repeated muscular contractions against relatively high loads can be beneficial in reducing risks for many chronic diseases.

Body composition and sports performance

Many athletes believe that they must be big to be good in their sports because size has traditionally been associated with performance quality in certain sports, such as American football, rugby, basketball, and baseball. The bigger the athlete, the better the

performance. But big doesn't always mean better. In certain sports, smaller and lighter are considered more ideal, i.e., gymnastics, figure skating, and diving. Yet, this can be taken to extremes, compromising the health of the athlete. The following sections are intended to discuss further how performance can be affected by body type, weight/size, and composition.

Somatotype

Somatotype concerns physical types or physique of the body. A simple observation of the track-and-field events at the Olympic Games suggests that the physical characteristics of those who are successful in the shot put are different from those who are successful in the marathon. Indeed, there exist different body types, some of which may be considered desirable for particular sporting events. According to William Sheldon (1898–1977), an American psychologist who devoted his life to observing the variety of human bodies and temperaments, each person could be characterized as possessing a certain amount of the following three components of body form:

Endomorph: relative predominance of soft roundness and large digestive viscera.

Mesomorph: relative predominance of muscle, bone, and connective tissue ultimately derived from the mesodermal embryonic layer.

Ectomorph: relative predominance of linearity and fragility with a great surface-to-mass ratio giving sensory exposure to the environment.

Most people are a mixture of these three body types, with a tendency toward one of them. Only 5 percent of the population are considered "pure" for each type. William Sheldon also examined 137 Olympic track-and-field athletes. He revealed that, although variation exists, a majority of athletes are considered to be between mesomorph and ectomorph. Via further analysis given by Heath and Carter (1967), it was reported that Olympic weight-lifters and throwers were mostly mesomorphic, but tended slightly toward endomorphic. On the other hand, most distance runners and basketball players are considered mainly ectomorphic. Indeed, each athlete's build is a unique combination of these three components. Athletes in certain sports usually exhibit a predominance of one component over the other two. For example, body builders exhibit primarily mesomorph or muscularity, basketball centers exhibit primarily ectomorph or linearity, and sumo wrestlers exhibits primarily endomorph or fatness.

A predominantly endomorphic individual typically has short arms and legs and a large amount of mass on their frame. This hampers their ability to compete in sports requiring high levels of agility or speed. Sports of pure strength, like power lifting, are perfect for an endomorph. Their extra weight can make it difficult to perform sustained weight-bearing aerobic activities such as running. They can gain weight easily and lose condition quickly if training is ceased.

A predominantly mesomorphic individual excels in strength, speed, and agility. Their medium structure and height, along with their tendency to gain muscle and strength easily, makes them a strong candidate for a top athlete in almost any sport. They respond well to cardiovascular and resistance training due to their adaptability and responsive physiology. They can sustain low body fat levels and find it easy to lose and gain weight.

A predominantly ectomorphic individual is long, slender, and thin, and therefore may not be suitable for power and strength sports. While they can easily grow lean and hard, their lack of musculature severely limits their chances in sports requiring mass.

Typically, ectomorphs dominate endurance sports, such as distance running and cycling. However, they can archive low levels of body fat which may be detrimental to health and for females in endurance sports it may result in a cessation of periods and iron deficiency. Table 14.6 summarizes the physical characteristics and sports benefits of the three somatotypes.

Body fatness and performance

Relative body fat or percentage of body fat is a major concern for athletes. Adding more fat to the body just to increase the athlete's weight and overall size is generally detrimental to performance. Many studies have shown that the higher the percentage of body fat, the poorer the person's athletic performance. This is true of all activities in which the body's weight must be moved through space, such as running and jumping. A negative association between level of fatness and sports performance has been demonstrated for a wide variety of sports events relating to speed, endurance, jumping ability, and balance and agility. In general, leaner athletes perform better.

Body composition can profoundly influence running performance in highly trained distance runners. Less fat generally leads to better performance. Early studies have demonstrated that male and female long-distance runners of national and international caliber averaged 4.3 and 15.2 percent of body fat, respectively (Pollock *et al.* 1977, Wilmore and Brown 1974). These values are similar to the more recent reports of elite male and female Kenyan endurance runners who averaged 6.6 and 16 percent of body fat, respectively (Billat *et al.* 2003). In terms of gender comparisons, male runners normally have much less relative body fat than female runners; this is thought to be one of the most important reasons for the differences in running performance between elite male and female distance runners. This contention is supported by a study of male and female runners who, when matched by their 24-km road race time, did not differ in relative body fat (Pate *et al.* 1985). For body dimension and structure, distance runners generally have smaller girths and bone diameters than their untrained counterparts. The best long-distance runners possess an overall smaller body frame, including both stature and skeletal dimension. This will then ensure that much less weight would need to be carried in running long distances. Runners with extra weight added to their trunks have been shown to increase their metabolic cost of submaximal exercise and to reduce their maximal aerobic power (Cureton and Sparling 1980). On the other hand, runners with ectomorphic predominance and lighter limbs have been linked to greater running economy or efficiency (Wilber and Pitsiladis 2012).

Male and female competitive swimmers generally have more body fat than distance runners. Male swimmers who competed in the Tokyo and Mexico City Olympics were found to have an average body fat of 12 and 9 percent, respectively. It was speculated that because of a lower core temperature due to cool water of the training environment, swimmers tend to have an increased appetite, which is often not the case in athletes who are trained on land. In a study that compared collegiate swimmers and runners, Jang *et al.* (1987) found that female swimmers consumed a greater amount of energy (2490 kcal) than female runners (2040 kcal). However, they failed to demonstrate the difference in energy intake between male swimmers (3380 kcal) and male distance runners (3460 kcal). Swimming is a weight-supported event. Although the athletes move their own body mass, swimmers are supported by the buoyancy of the water, reducing energy cost associated with this movement. It is sometimes argued that a certain level of body fat is useful for the swimmer owing to enhanced buoyancy and body position or a reduced drag due to more rounded body surfaces. In analyzing the correlation between swimming performance and the physical characteristics of a large group of female

Table 14.6 Physical characteristics of somatotypes and their suitability in sports

Somatotype	*Physical characteristics*	*Sports benefits*
Endomorph	• A pear-shaped body • Wide hips and shoulders • Wider front to back rather than side to side • High fat mass and fat-free mass	• Size benefits sports such as football or rugby where bulk is useful given that it can be moved powerfully • Often associated with larger muscle mass compared with ectomorphs • Tend to have large lung capacity which can make them suited to sports such as swimming or rowing
Mesomorph	• A wedge-shaped body • Wide, broad shoulders • Narrow hips • Narrow front to back rather than side to side • Low or normal fat mass and high fat-free mass	• Respond well to cardiovascular and resistance training • Can easily gain or lose weight depending on the sports' needs • Often associated with low body fat and high fat-free mass, which is suitable for all sports events
Ectomorph	• Narrow shoulders and hips • A narrow chest and abdomen • Thin arms and legs • Low normal fat mass and low fat-free mass	• Light frame makes them suited to aerobic activity such as long-distance running or gymnastics • A larger body surface area-to-mass ratio enhances their heat tolerance

swimmers aged from 12 to 17, Stager *et al.* (1984) found that fat-free mass was still a better predictor of swimming performance than body fat.

Resistance-trained athletes, particularly body builders and Olympic weight-lifters, exhibit remarkable muscular development and a relatively lean physique. These athletes possess a large fat-free mass because percentages of body fat measured by hydrostatic weighing averaged 9.3 percent in body builders and 10.8 percent in Olympic weight-lifters (Katch *et al.* 1980). However, using the weight–height tables, about 20 percent of these athletes would be classified as overweight. Interestingly, among weight-lifters, adding extra fat weight is sometime considered advantageous. Some weight-lifters add large amounts of fat weight immediately before a competition under the premise that the additional weight will lower their center of gravity and give them a greater mechanical advantage in lifting, although this practice has not yet been confirmed with the use of a scientific approach. The sumo wrestler is another notable exception to the notion that overall body fat may not be a major determinant of athletic success. In this sport, the larger individual has an advantage toward winning, but, even so, the wrestler with the higher fat-free mass should have the best overall success.

Body weight and composition has always been an intriguing issue among American football players because American football is a game that emphasizes the importance of size of athletes to be successful. This is especially true for football linemen. The results of body composition analysis for the American professional football players conducted by Welham and Behnke in 1942 appear to be quite acceptable by today's standards. For example, the players as a group had a body fat content that averaged only 10.4 percent of body mass, while fat-free mass averaged 81 kg (or 179 lb). In addition, the heaviest lineman weighed about 118 kg (or 260 lb) and had 17.4 percent body fat, whereas the lineman with the most body fat (23.2 percent) weighed 115 kg (or 252 lb). During the past 70 years, however, there has been a steady increase in body weight, especially in defensive and offensive linemen. For example, according to the National Football League, the average body weight of linemen reached 127 kg (or 280 lb) by 1995. Collegiate linemen are also increasing in size. In a large study of collegiate athletes evaluating size, football linemen were found to have the largest increase in weight and body mass index (Yamamoto *et al.* 2008). A study by Borchers *et al.* (2009) also showed an average body fat of 17.3 percent in Division I collegiate football players, with linemen exhibiting the highest body fat percentages (25.6%). Both defensive and offensive linemen would have a decided advantage of being big and strong in the game of American football. However, this group of athletes has been associated with increased risks of cardiovascular diseases and high prevalence of metabolic syndrome and insulin resistance.

There are a number of sports in which competitions are conducted with weight limits or weight classes, such as Olympic weight-lifting, boxing, and wrestling. In these sports, weight classes are designed to promote competition among athletes of roughly equal size. In this case, body mass is considered a proxy for fat-free mass or muscle mass and, therefore, the athlete's strength and power. Despite such intention to promote fair and interesting competition by matching opponents of equal size and capability, the prevailing attitude in these sports is that the athletes will gain a performance advantage by competing against smaller and lighter opponents in a weight class that is lower than his natural training weight. Typically, the athlete aims to reduce his body mass to the lowest level possible, with much of this effort taking place in the days before a competition. The rapid weight loss tactics used by athletes to successfully weigh in at a lower weight class are commonly referred to as "making weight." The medical and scientific communities have been concerned over problems in athletes associated with making weight. In a survey that involved 63 collegiate wrestlers and 368 high school wrestlers, Steen and Brownell (1990) found that the athletes lost weight on average 15 times during a normal

season, and the average for the most weight lost at any one time was 7.2 kg (or 15.8 lb). A variety of aggressive methods have been used by these athletes to lose weight, and they include dehydration, food restriction, fasting, and, for a few, vomiting, laxatives, and diuretics. In addition, "making weight" was associated with fatigue, anger, and anxiety, and over one-third of the wrestlers, at both the high school and college level, reported being preoccupied with food and eating out of control after a match.

Establishing an appropriate weight goal

In light of the previous discussion, athletes could be pushed well below the optimal body weight range. Therefore, it is critically important to properly set weight standards. Body weight standards should be based on an athlete's body composition. Once body composition is known, the athlete's fat-free mass may then be determined and used to estimate what the athlete should weigh at a specific percentage of body fat. Table 14.7 illustrates how to determine weight goal for a female athlete who weighs 75 kg and wants to reduce her body fat from 20 to 15 percent. We know her goal weight will consist of 15 percent fat mass and 85 percent fat-free mass, so in order to estimate her weight goal at 15 percent body fat we divide her current fat-free mass by 85 percent, which is the fraction of her weight goal that is to be represented by her fat-free mass. The calculation yields a goal weight of 70.6 kg, which means that she needs to lose 4.4 kg. This method allows a determination of weight goal based on the assumption that the fat-free mass stays unchanged despite a loss of body weight. Table 14.8 provides gender-specific ranges of body fat percentage for various sports, which may be used to determine an athlete's relative fat goal. In most cases, these values represent elite athletes in those sports. Given that body fat is considered a performance inhibitor in almost all sports, the values presented in Table 14.8 may also be used to evaluate the training status of athletes competing in various sporting events.

Body composition assessments

It is clear that measurements of body composition are necessary and important because the percentages of body fat, as well as its placement, can have profound effects on health and performance. Estimating body fat content is a routine practice in assessing one's nutritional status. It is also part of a comprehensive health-, fitness- and sports-related assessment. Desirable body fat is deemed important for the health and wellness of all individuals. As already noted, excessive body fat is related to increased risk of cardiovascular, metabolic, pulmonary, and neuromuscular diseases. Body composition is an important factor in most athletic events. A competitive edge may be gained by the athlete who can achieve the optimal balance between fat and fat-free mass for his or her

Table 14.7 Example of computing a weight goal

Parameter	*Results*
Current weight	75 kg
Percentage of body fat	20
Fat weight	15 kg (weight × 20%)
Fat-free weight	60 kg (weight – fat weight)
Relative fat goal	15% (or 85% fat-free mass)
Weight goal	70.6 kg (fat-free mass ÷ 85%)
Weight loss goal	4.4 kg (current weight – weight goal)

Table 14.8 Ranges of body fat percentages for male and female athletes of selected sports

Sports	*Men*	*Women*
Baseball/softball	8–14	12–18
Basketball	7–11	21–27
Body-building	5–8	6–12
Cycling	5–11	10–16
American football (backs)	9–12	–
American football (linebackers)	11–14	–
American football (linemen)	14–18	–
American football (quarterbacks)	11–14	–
Gymnastics	5–12	8–16
Field hockey	8–16	12–16
Rowing	11–15	–
Rugby	6–16	–
Skiing (alpine)	7–14	18–24
Skiing (cross-country)	8–13	16–22
Soccer	7–13	10–18
Swimming	6–12	18–22
Tennis	8–16	18–22
Track-and-field (field events)	10–18	18–24
Track-and-field (sprint)	8–14	12–18
Track-and-field (long distance)	4–10	10–16
Track-and-field (jump)	5–10	8–14
Triathlon	5–12	8–15
Volleyball	7–15	10–20
Olympic weight-lifting	5–12	10–18
Wrestling	5–15	–

Source: adapted from McArdle *et al.* (2009); Powers and Howley (2009); Wilmore and Costill (2004).

particular sport. Too low a percentage of body fat can adversely affect metabolism and health. Female athletes with overtly low body fat can suffer from conditions of amenorrhea and osteoporosis, which are often accompanied by an eating disorder such as anorexia nervosa. The major reasons why practitioners, clinicians, and researchers conduct body composition assessment are summarized as follows:

- To monitor nutrition.
- To assess risk factors for diseases.
- To evaluate overall health- and sports-related fitness.
- To track changes in body composition in response to an intervention program.
- To advance research regarding the impact of body composition upon health and performance.
- To set safety standards.

Dozens of methods have been developed within the past few decades and are currently used in clinical, fitness, and athletic settings. These methods vary considerably in their accuracy, required instruments, and practicality. Each method is associated with advantages and disadvantages, and in general there is a trade-off between accuracy and practicality. The following provides a review on methods commonly used for assessing body composition.

Laboratory methods for assessing body composition

In many laboratory and clinical settings, **densitometry** and dual-energy X-ray absorptiometry are used to obtain reference measures of body composition. Due to the high precision and reliability of these two techniques, they are also often used in research settings. For densitometric methods, total body density (Db) is estimated from the ratio of body mass (BM) to body volume (BV) (i.e., Db = BM ÷ BV). Body volume can be determined by hydrostatic weighing or air replacement plethysmography. As mentioned earlier in this chapter, once body density is known, the percentage of body fat can be calculated using either the Brozek or the Siri equation.

Hydrostatic weighing

Hydrostatic weighing is a valid, reliable, and widely used technique to determine whole-body density (Wang *et al.* 2000). The technique determines body volume by measuring the volume of water displaced by the body. According to the **Archimedes' principle**, weight loss under water is directly proportional to the weight of water displaced by the body (Figure 14.3). Such a measure of weight, however, must be converted into volume. As water density equals 1 under normal circumstances (i.e., warm water temperature of 34 to 36°C), the weight of water is quantitatively the same as the volume of water. Therefore, by weighing a subject under water, his or her body volume may be determined. **Body density** can be calculated using the following formula:

$$\text{Body density} = WA/BV = WA/[(WA - \text{Net UWW})/DW - (RV + GV)]$$

Where WA = body weight in air; BV = body volume; UWW = body weight submerged in water; DW = density of water; RV = residual lung volume; GV = volume of gas in the gastrointestinal tract.

This approach is based on the two-compartment model of body composition: fat and fat-free mass. It assumes a constant fat mass density of 0.90 g/cm^3 and a density of fat-free mass of 1.10 g/cm^3. The densities of bone and muscle tissue are greater than the density of water (density of distilled water = 1.00 g/cm^3), whereas fat is less dense than water. Thus, a muscular subject having a low percentage of body fat tends to weigh more

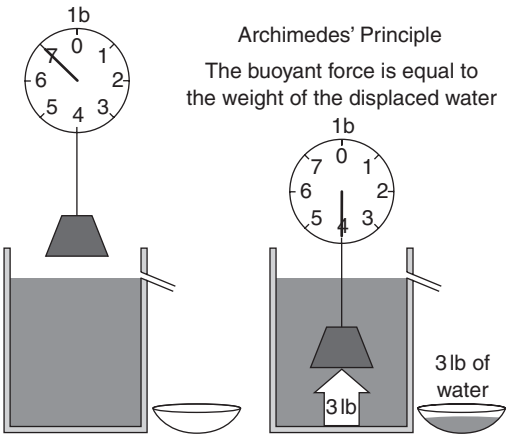


Figure 14.3 Illustration of the Archimedes' Principle

when submerged in water than do subjects having a higher percentage of body fat. Caution should be taken with regard to these assumptions. As mentioned earlier, the density of fat-free mass varies among individuals. Athletes, for example, tend to have denser bone and muscle tissue, whereas older individuals tend to have less dense bones. It has been reported that hydrostatic weighing has a tendency to underestimate body fat for athletes (possibly even negative body fat values) and overestimate body fat for the elderly (Brodie 1988).

To measure underwater weighing, one may use a tank, tub, or pool of sufficient size for total body submission and a chair or platform attached to electronical load cells (Figure 14.4). The water should be comfortably warm, filtered, chlorinated, and undisturbed by wind or other activity in the water during testing. It is important to note that the Archimedes' principle applies to the condition where there is minimal movement in the body relative to the surrounding water. This may be more easily achieved in an isolated water tank. However, a large amount of error may occur when underwater weighing is conducted in a pool. When measuring with a pool, it is suggested to use a wooden shell to reduce water movement, thereby enhancing precision.

Please note that the net underwater weight (UWW) as shown in the formula above is the difference between UWW and the weight of the equipment such as the chair or platform and its supporting device. The BV must be corrected for the volume of air remaining in the lungs after a maximal expiration, which is residual volume or RV, as well as the volume of air in the gastrointestinal tract (GV). The GV is assumed to be 100 ml (Heyward 2002). The RV is commonly measured using helium dilution, nitrogen washout, or oxygen dilution techniques, although it can also be predicted based on the subject's age, gender, and height. In adult men, this value is between 1.5 to 2 liters depending on body size. For women, values are somewhat lower due to their smaller size.

Hydrostatic weighing has been considered the good standard against which other body composition estimates are validated. There are, however, distinct limitations associated with this method. It is inappropriate for settings that cannot house a 1000-gallon

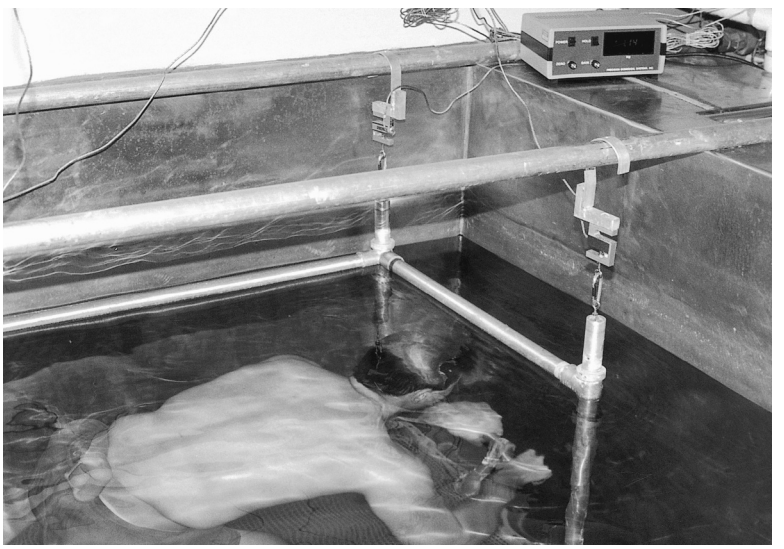


Figure 14.4 Hydrostatic weight using electronic load cells and platform

Source: Heyward (2010). Used with permission.

tank. The tank must be cleaned and disinfected regularly, and the tank water must be maintained within a range of acceptable temperatures, because the density of water varies with temperature. The method requires the determination of residual lung volume, which can be technically challenging. Because air density is zero, even a small error in the estimate of air volume can significantly affect the calculation of body density. Hydrostatic weighing may not be used with persons who are afraid of total immersion in water, especially considering that the procedure requires forcible exhalation while submerged. Neither is it an appropriate method for persons with certain pulmonary disorders, such as asthma and emphysema. In addition, special adjustments must be made for morbidly obese persons who tend to float in water; they often have to wear weights to keep them underwater.

Air displacement plethysmography

As an alternative to underwater weighing, body volume and, consequently, body density and percentage of body fat can be measured by a technique known as **air displacement plethysmography**. Compared to hydrostatic weighing, this method is relatively expensive, requiring the use of a whole-body plethysmography (i.e., Bod Pod). The Bod Pod is a large, egg-shaped fiberglass shell (Figure 14.5). The molded front seat separates the unit into a front and rear chamber. The electronics, housed in the rear of the chamber, include pressure transducers, breathing circuit, and an air circulation system. The technique uses

Figure 14.5 Air displacement plethysmograph

Boyle's law, which states that at a constant temperature for a fixed mass, the product of pressure and volume of a gas is a constant and pressure and volume are inversely proportional. Mathematically, Boyle's law can be expressed as PV=k, where P is the pressure of the gas, V is the volume of the gas, and k is constant. For comparing the same substance under two different conditions, the law may be usefully expressed as $P_1V_1=P_2V_2$. The equation shows that, as volume increases, the pressure of the gas decreases in proportion. Similarly, as volume decreases, the pressure of the gas increases.

This relationship allows for the derivation of an unknown volume by directly measuring pressure. During a measurement, the Bod Pod produces very small volume changes inside the chamber and measures the pressure response to these small volume changes. To accomplish this, the interior volume of the empty Bod Pod chamber is first determined, and the volume, once the subject is seated inside the Bod Pod, is also determined. The subject's volume is obtained by subtraction. For example, if the interior air volume of the empty chamber is 400 liters and the volume of the chamber is reduced to 350 liters with the subject inside, then the body volume of the subject is 50 liters.

Using this method, the thoracic gas volume, which includes all air in the lungs and airway, is measured instead of residual lung volume. The measurement uses the same principle of the pressure–volume relationship. During this measurement, the subject's nostrils are sealed with a nose clip, and the subject is instructed to breathe quietly through a single-use, disposable breathing tube that connects to a breathing circuit housed in the unit's rear chamber when the chamber remains closed. After several normal breaths, a valve in the breathing circuit is momentarily closed at the mid point of an exhaustion. The subject compresses and then relaxes the diaphragm muscle. This produces small pressure fluctuations, which are measured and used to calculate the thoracic air volume.

Compared to hydrostatic weighing, this method is quick, usually taking between five and ten minutes to complete. It is also relatively simple to operate, and can accommodate those who are obese, elderly, disabled, as well as those who are afraid of total immersion in water. Limited demands are placed on the subject as the procedure does not require maximal exhalation in order for the residual volume to be used for calculation. The Bod Pod is mobile so that it can be moved from one location to another. In addition, this method requires minimal training and equipment maintenance.

Despite the fact that air displacement plethysmography overcomes some of the methodological and technical constraints of hydrostatic weighing, more studies seem to be necessary to continue validating this method. Some studies, especially when using a heterogeneous group of healthy adults, have reported good test-retest reliability and validity compared to hydrostatic weighing (McCrory *et al.* 1995, Vescovi *et al.* 2001). However, this method has been questioned for its validity in assessing body composition among athletes, children, and different ethnic subgroups. For example, the Bod Pod was found to underestimate percentage body fat in children (Lockner *et al.* 2000). It was also reported that this method underestimated percentage body fat in collegiate football players (Collins *et al.* 1999) and over-predicted percent body fat in collegiate track-and-field female athletes (Bentzur *et al.* 2008). In addition, this method was found to overestimate percent body fat of African American men (Wagner *et al.* 2000).

Dual-energy X-ray absorptiometry

Dual-energy X-ray absorptiometry (DEXA) is gaining in popularity as a standard technique for measuring body composition. This technique was initially developed for the measurement of bone density. Because this technique can also identify soft tissue and categorize it as fat or lean mass, there has been a great deal of interest in using DEXA

for assessing relative body fat content. The DEXA system generates two X-ray beams with differing energy levels that can penetrate bone and soft tissue. The procedure involves a series of cross-sectional scans from head to toe at 1-cm intervals, and body composition is determined based on differential photon absorption of bone minerals and soft tissue. An entire DEXA scan takes approximately 10 to 20 minutes depending on body size. Computer algorithms reconstruct the attenuated X-ray beams to produce an image of the underlying tissue and quantify bone mineral density, fat content, and fat-free mass for the whole body as well as for various sections of the body, including the head, truck, hips, and limbs (Figure 14.6).

DEXA is precise, accurate, and reliable. Its measurements are based on a three-compartmental model – that is, bone mineral, fat mass, and soft lean mass – rather than on a two-compartmental model as in most other methods. In this context, DEXA can provide accurate assessments of fat and fat-free mass in individuals with below- and above-average bone mineral density. DEXA requires little effort and cooperation from the subjects and, as such, the method will be suitable to a broader range of individuals, including those who are very young, very old, or diseased. A single scan produces regional and whole-body estimates of fat and fat-free mass. By comparing regional fat content in the trunk and limbs, clinicians and researchers can also obtain information with regard to body fat distribution of the subject. There is a high degree of agreement between percentage body fat estimates obtained by hydrostatic weighing and by DEXA.

DEXA has some limitations. The equipment is expensive, and often requires trained radiology personnel to operate. As differences in hydration of lean tissue can produce errors in estimating body composition, concerns have been raised about the appropriateness of using DEXA for assessing body composition in individuals with acute or chronic changes in body water (Elowsson *et al.* 1998). In addition, DEXA measurements of body composition are sensitive to the anterior-posterior thickness of the body or body parts, so that results may be confounded by the size and shape of an individual (Roubenoff *et al.* 1993).

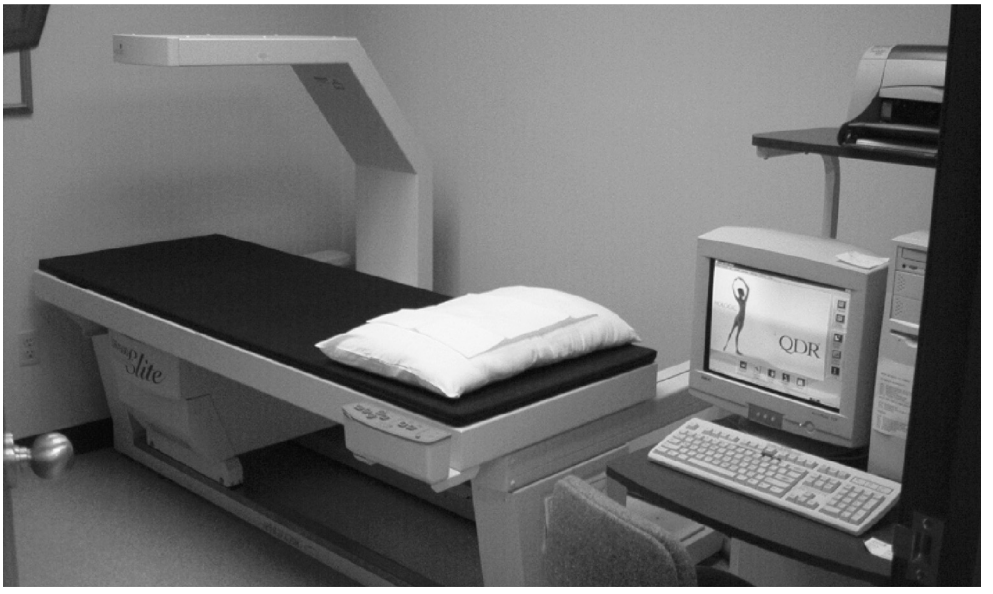


Figure 14.6 Dual-energy X-ray absorptiometer

Field methods for assessing body composition

While laboratory methods are commonly used to assess fat mass, field measures, such as skinfold thickness and bioelectrical impedance, may be more practical for screening large numbers of individuals within a short period of time. These methods are relatively inexpensive and simple to perform. In order to use these methods appropriately and to produce results that are reasonably accurate and reliable, one should understand the basic assumptions and rationale as well as potential sources of error associated with each method. A sufficient practice is also necessary in order to ensure measurement accuracy and reliability.

Skinfold method

The **skinfold** method is probably the most frequently used of all body composition methods. A skinfold is a double fold of skin and the immediate layer of subcutaneous fat and is measured in millimeters by a special tool called a caliper. The accuracy of skinfold measurements is affected by the type of caliper used. The three calipers shown in Figure 14.7 operate on the same principle as a micrometer that measures the distance between two points. However, Lange and Harpenden, which cost several hundred dollars, are considered the better choices compared with plastic calipers in terms of yielding reasonably reliable skinfold results. These calipers exert constant pressure across the entire range of skinfold thickness. On the other hand, the plastic calipers tend to be most accurate through the middle range of percent body fat; the measurements of very thin and very thick skinfolds are most likely to be inaccurate.

There are more than 100 equations available for estimating percent body fat from skinfold thickness (Heyward 2002). These equations differ by number and location of skinfold sites. They also differ in terms of populations being used for developing the equation. Some of them are quite general, meaning that equations may be used for any healthy adult within the same gender. Others are more specific and were developed for relatively homogeneous subgroups of populations. The population-specific equations are assumed to be valid only for subjects who have similar characteristics, such as age, gender, ethnicity, or level of physical activity. For example, the equation derived from adults would not be valid for use among children and adolescents. Generally speaking, in a research setting, a seven-site procedure is most often adopted, with measurements taken by Harpenden or Lange calipers. In clinical or field settings, four-site, three-site, and even two-site procedures are more commonly chosen. In these settings, the loss of accuracy due to the use of fewer

Figure 14.7 Common skinfold calipers. The Lange and Harpenden calipers provide constant tension at all jaw openings

skinfold sites is largely compensated by the gain in practicality. It is also recommended to use equations that have skinfolds measured from a variety of sites, including both upper and lower body regions (Martin *et al.* 1985). Table 14.9 presents some of the commonly used generalized skinfold equations for predicting body density. These questions allow for calculation of body density, with the latter being converted into percent body fat using either the Brozek or the Siri equation as previously discussed.

To reduce error, skinfold sites should be precisely determined and, in some cases, marked for enhancing repeatability. The following describes eight most commonly used skinfold sites as outlined in the *Anthropometric standardization reference manual* (Lohman 1988):

- Chest: measure with a diagonal skinfold midway between the right nipple and anterior axillary line (imaginary line dropping straight down from the front of the armpit).
- Triceps: measured with a vertical skinfold at the posterior midline of the right upper arm over the triceps midway between the lateral projection of the acromion process of the scapula and the inferior margin of the olecranon process of the ulna.
- Subscapular: measured at 1 cm below the lowest angle of the scapula on the diagonal fold that runs from the vertebral border downward.
- Midaxillary: measured with a horizontal skinfold at the right midaxillary line (a vertical line extending from the middle of the axillar) level with the xiphisternal junction.
- Suprailliac: measured at just above the crest of the right illum on a diagonal skinfold that runs from the anterior axillary line downward.
- Abdomen: measured with a horizontal fold at approximately 2 cm to the right of and 1 cm below the mid point of the umbilicus.
- Thigh: measured with a vertical skinfold at the midline of the anterior aspect of the thigh midway between the junction of the midline and the inguinal crease and the proximal border of the patella.
- Medial calf: measured with a vertical skinfold at the point of maximal circumference and medial aspect of the calf.

The technique of measuring a skinfold is the same regardless of the equations being used to assess body composition. The accuracy and reliability of measurement depends largely on the skill of the examiner. Examiners can improve the accuracy of results by training with an experienced and skilled technician, practicing on clients of different body types, carefully identifying and marking skinfold sites, and following standardized procedures. In addition, because the conversion from skinfolds to body fatness is influenced by ethnicity, gender, and age, it is especially important to use an appropriate prediction equation for the individual being tested. Skinfold measurements, when taken properly, correlate highly ($r = 0.83–0.89$) with hydrostatic weighing, with a standard error of approximately 3 to 4 percent. This error should always be kept in mind when using tables or equations to convert skinfold thickness into percent body fat. Because of such potential error, researchers often choose to stay with the skinfold thickness measurement rather than convert it into percent body fat, especially when repeated measurements are made of the same subject.

The following are the general guidelines for taking the skinfold measurement:

- All skinfolds should be taken on the right side of the body.
- Grasp the skinfold firmly between the thumb and index finger of the left hand, with the thumb and index finger being placed about 1 cm above the skinfold site. It is important to lift only skin and fat tissue, not muscle.

Table 14.9 Generalized equations for predicting body density (Db) for adult men and women

Gender	*Skinfold sites*	*Equations*
Men	7 sites (chest, midaxillary, triceps, subscapula, abdomen, suprailiac, thigh)	$Db = 1.112 - 0.00043499(\Sigma 7 \text{ skinfolds}) + 0.00000055\ (\Sigma 7 \text{ skinfolds})^2 - 0.00028826\ (\text{age})$
	4 sites (abdomen, suprailiac, triceps, thigh)	$Db = 0.29288\ (\Sigma 4 \text{ skinfolds}) + 0.0005\ (\Sigma 4 \text{ skinfolds})^2 + 0.15845\ (\text{age}) - 5.76377$
	3 sites (chest, abdomen, thigh)	$Db = 1.10938 - 0.0008267\ (\Sigma 3 \text{ skinfolds}) + 0.0000016\ (\Sigma 3 \text{ skinfolds})^2 - 0.0002574\ (\text{age})$
Women	7 sites (chest, midaxillary, triceps, subscapula, abdomen, suprailiac, thigh)	$Db = 1.097 - 0.00046971(\Sigma 7 \text{ skinfolds}) + 0.00000056\ ((\Sigma 7 \text{ skinfolds})^2 - 0.00012828\ (\text{age})$
	4 sites (abdomen, suprailiac, triceps, thigh)	$Db = 0.29669\ (\Sigma 4 \text{ skinfolds}) + 0.00043\ (\Sigma 4 \text{ skinfolds})^2 + 0.02963\ (\text{age}) - 1.4072$
	3 sites (triceps, suprailiac, thigh)	$Db = 1.0994921 - 0.0009929\ (\Sigma 3 \text{ skinfolds}) + 0.0000023\ (\Sigma 3 \text{ skinfolds})^2 - 0.0001392\ (\text{age})$

Sources: Jackson *et al.* (1980); Jackson and Pollock (1978).

- Do not take measurements when the subject's skin is moist because there is a tendency to grasp extra skin, obtaining inaccurately large values. Also, do not take measurements immediately after exercise or when the subject being measured is overheated because the shift of body fluid to the skin may expand normal skinfold thickness.
- The skinfold is lifted by placing the thumb and index finger on the skin about 8 cm (or 3 in) apart and perpendicular to the desired skinfold. However, for individuals with extremely large skinfolds, the starting separation between the thumb and index finger should be greater than 8 cm in order to lift the fold.
- Keep the fold elevated when the caliper is being applied to the skinfold site. The caliper jaws should be placed perpendicular to the long axis of the skinfold and about midway between the base and crest of the skinfold, and jaw pressure is then released slowly.
- The measurement should be read within two seconds after the caliper pressure is applied, and should always be repeated two to three times so that an average skinfold value is recorded for each site.
- Upon completion, open the caliper jaws before remove the caliper from the skinfold site.

Bioelectrical impedance analysis

Bioelectrical impedance analysis (BIA) measures body composition based on the understanding that lean tissue, owing to its higher water content, is a much better conductor of electricity than fat tissue, which contains considerably less water. In BIA, an electronic instrument generates a low-dose and harmless current (800 μA at 50 kHz), which is passed through the person being measured. BIA determines the electrical impedance, or opposition to the flow of this electric current. This information is then used to estimate total body water and fat-free mass. Figure 14.8 demonstrates two examples of bioelectrical impendence analyzers, which have also been marketed for home use. The Tanita analyzer measures lower body resistance between the two legs as the individual stands on the electrode plates. The Omron analyzer, which is handheld, measures upper body resistance between the two arms.

There are a wide variety of BIA equations available for predicting fat-free mass and percent body fat. These prediction equations are based on either population-specific or generalized models, which may be found in the book by Hayward and Stolarczyk (1996). Early models of BIA instruments simply provide the operator with a value of resistance, which requires further calculation that uses an appropriate equation to determine the subject's percent body fat. However, most of the current and more sophisticated BIA instruments now contain some prediction equations to be selected along with a computer and printer, which have made data analysis much easier. In general, it has been recommended not to use the fat-free mass and percent body fat estimates obtained directly from the BIA instrument unless the equations are known to apply directly to the subjects being measured. In other words, one can obtain a value of resistance from the analyzer and then look for an appropriate equation for converting the resistance into percent body fat. The prediction equations are valid only for subjects whose physical characteristics are similar to those specified in the equation.

BIA has the advantage of being safe, quick, portable, and easy to use. It requires little or no technical knowledge or skills of the operator or the client. It is less intrusive as compared to the hydrostatic weighing and skinfold measurement. When the proper measurement guidelines are followed and the appropriate BIA equation is used, results of BIA have been found to have about the same accuracy as the skinfold method.

Figure 14.8 Common bioelectrical impendence analyzers

The major disadvantage is that BIA assumes that subjects are normally hydrated when such an assumption is often incorrect. The state of hydration can greatly affect the accuracy of BIA. This is because any change in bodily water can alter normal electrolyte concentrations, which in turn affect the flow of electrical current independent of a real change in body composition. For example, dehydration caused by insufficient water intake, excessive perspiration, heavy exercise, or caffeine or alcohol use will lead to an overestimation of body fat content by increasing bioelectrical impedance. To prevent this, subjects should be advised to refrain from consuming caffeine and alcohol 24 hours before testing and to avoid heavy exercise 12 hours before testing. It is also recommended that BIA measurements be made in a room with normal ambient temperature and that no testing be given to anyone who is on diuretic medications within seven days of the test, or female subjects who perceive that they are retaining water during the stage of their menstrual cycle.

Circumference measurements

Measuring girth or **circumference** represents another category of anthropometric methods in addition to measuring skinfold and skeletal breadth as discussed earlier in this chapter. Methods are available that involve measuring circumference for assessing body composition (Weltman *et al.* 1987, 1988, Tran and Weltman 1988). In fact, in comparison with skinfold technique, measures of circumference are considered more accurate and feasible for use in obese individuals where conducting a skinfold test is often difficult and sometimes impossible (Seip and Weltman 1991). Circumference measurements are also useful in clinical settings. For example, measurements of waist circumference and the ratio of waist to hip circumference can help distinguish between

patterns of fat distribution in the upper and lower body. They provide an important indication of disease risk. As shown in Table 14.3, a waist circumference larger than 102 cm in men or 88 cm in women is considered a risk factor independent of obesity. Likewise, young adults with a waist-to-hip ratio larger than 0.94 for men and 0.82 for women are at high risk for adverse health consequences (Bray and Gray 1988). Waist circumference reflects the abdominal fat accumulation. It is considered that fat stored in this region is more responsible for the pathological processes that cause insulin resistance, type 2 diabetes, and heart disease.

Using measures of circumference to assess body composition has its unique advantage in testing that involves obese individuals. When studying obese populations, it is often difficult to obtain accurate skinfold measurements because (1) the skinfold may exceed the maximum opening capacity of the caliper; (2) caliper tips may slide on large skinfold; and (3) readings tend to decrease with subsequent measurements due to repeated compression of the subcutaneous fat. To overcome these shortcomings associated with the skinfold method, Weltman *et al.* (1987, 1988) developed and cross-validated body composition prediction equations for obese men and women using height, weight, and measures of waist and abdomen circumference as predictor variables. These gender-specific equations are listed as follows:

$$\text{Obese men: } \%\,\text{fat} = 0.31457(\text{mean abdomen}) - 0.10969(\text{Wt}) + 10.8336$$

$$\text{Obese women: } \%\,\text{fat} = 0.11077(\text{mean abdomen}) - 0.17666(\text{Ht}) + 0.14354(\text{Wt}) + 51.03301$$

In these equations, mean abdomen = the average of two circumferences measured at waist and abdomen, Wt = weight, and Ht = height. Waist circumference is determined by placing the tape in a horizontal plane at the level of the narrowest part of the torso as seen from the anterior aspect. The abdomen circumference is determined by placing the tape at the level of the umbilicus. Both measurements are taken at the end of a normal expiration.

Circumferences should be measured by using an anthropometric tape, which is made from flexible material that does not stretch with use. Some anthropometric tapes have a spring-loaded handle that allows a constant tension to be applied during the measurement. The examiner should hold the zero end of the tape in the left hand, just above or below the remaining tape held in the right hand. The tape should be snug around the body part without indenting the skin or compressing subcutaneous adipose tissue. Duplicate measurements should be taken, and the circumference measurement should be recorded to the nearest half centimeter or quarter inch. Compared to the skinfold technique, skill is not a major source of measurement error. However, examiners should practice sufficiently and to closely follow standardized testing procedures for locating measurement sites, positioning the anthropometric tape, and applying tension during the measurement.

Summary

- Weight–height tables provide a rough estimate of ideal weight for a given height. The lowest mortality in the United States is associated with body weights that are somewhat below average for a given group based on sex and stature. However, weight–height tables reveal little about an individual's body composition. Studies of athletes clearly show that being overweight does not necessarily coincide with excessive body fat.
- BMI relates more closely to body fat and health risk than simply body mass and stature. BMI may be used in conjunction with skinfold measurements or waist

circumference as an improved means of assessing increased risk in adults for heart disease, stroke, type 2 diabetes, and premature death. Still, BMI fails to consider the proportion of fat mass and fat-free mass.

- Total body fat consists of essential fat and storage fat. Essential fat contains fat present in bone marrow, nerve tissue, and organs and serves as an important component for normal biological function. Storage fat represents the energy reserve that accumulates mainly as adipose tissue beneath the skin and in visceral depots.
- Athletes generally have physical characteristics unique to their specific sport. Weight-lifters or field event athletes exhibit as primarily endomorph and have relatively large fat-free body mass and high percentage of body fat, whereas distance runners or basketball players are mainly ectomorphic and have the lowest fat-free mass and fat mass. Most athletes are considered mesomorphic and have greater muscle mass that allows them to excel in strength, speed, and agility.
- Percent body fat is a major concern of athletes. Many studies have shown that the higher the percentage of body fat, the poorer the person's athletic performance. This is true for all activities in which the body weight must be moved through space, such as running and jumping. A negative association between level of fatness and sports performance has been demonstrated for a wide variety of sports events relating to speed, endurance, jumping ability, and balance and agility.
- Densitometry involves measuring the density of the entire body usually by hydrostatic weighing, with body density being converted later into percent body fat using either the Brozek or the Siri equation. Hydrostatic weighing remains the laboratory standard, but the time, expense, and expertise needed is prohibitive for many clinical settings.
- Air displacement plethysmography also measures body density and thus body composition. Subjects better tolerate this method than hydrostatic weighing. This method requires less subject cooperation, and residual volume measurements are not needed. It is as accurate as hydrostatic weighing, but the equipment is relatively more complex and costly.
- Measurement of skinfolds is the most widely used method of indirectly estimating percentage of body fat. The equipment is inexpensive and portable. Measurements can be easily and quickly obtained, and they correlate well with body density measurements. However, proper measurement of skinfolds requires careful site selection and strict adherence to the guidelines.
- In comparison with skinfold technique, measures of circumference are considered more accurate and feasible for use in obese individuals in which conducting a skinfold test is often difficult and sometimes impossible. In addition, measures of waist circumference and the ratio of waist to hip circumference can help distinguish between patterns of fat distribution in the upper and lower body.

Case study: calculating ideal body weight

Michael, a 45-year-old business man, works for a consulting firm and has a frequent travel schedule. Lately, he has been experiencing a steady weight gain. He is 5 feet 8 inches tall and weighs 200 pounds and his body mass index is 30.5, which is considered borderline obesity. He decides to see a personal trainer to solve his weight problem. His first meeting with the personal trainer includes a body composition assessment using bioelectrical impedance analysis. This initial assessment reveals that he has a

body fat of 28 percent. He is unhappy with this result and decides to do something to lose weight. Via discussion with the trainer, he sets an initial goal to reduce his body fat from 28 to 20 percent while maintaining his lean body mass.

Questions

- What is Michael's current fat mass and lean body mass?
- How much should Michael weigh in order to reach his target of 20 percent body fat? In this case, how much fat does he need to lose?
- Considering that there are many other techniques available for assessing body composition, what are the unique advantages and disadvantages associated with the bioelectrical impedance analysis that was used by Michael's trainer?

Review questions

1 Why is important to assess the body composition of your client or an athlete?
2 Explain the differences between essential and storage fat. How do they differ between males and females?
3 Explain the differences between visceral and subcutaneous fat.
4 Take a 20-year-old college male, 180 lb, 28 percent fat. What is his target body weight to achieve 17 percent fat?
5 Define body density. How is this parameter computed? How is body density related to percentage of body fat?
6 What is the Siri equation? Explain the assumptions that were used in developing the equation.
7 How is the body mass index (BMI) calculated? What are the advantages and disadvantages of using BMI in assessing body composition? Provide two scenarios where BMI and percentage don't agree each other.
8 Explain how BMI and waist circumference may be used to identify clients at risk due to obesity. Why is waist circumference considered more than BMI in predicting health risks?
9 Explain the Archimedes' principle. How is this principle used in hydrostatic weighing that measures one's body composition? What are the potential errors that can cause this technique to be inaccurate?
10 Describe Boyle's law. How is this law applied in the Bod Pod technique that measures one's body composition?
11 To obtain accurate estimates of body composition using the BIA method, your client must follow the pre-testing guidelines. Identify these client guidelines.
12 Describe the three gender-specific skinfold sites and their anatomical locations involved in the Jackson and Pollock equations. What were the assumptions made for the skinfold technique to be used to predict one's percentage of body fat?
13 Identify potential sources of measurement error for the skinfold method.
14 How would you rate the skinfold, BIA, and hydrostatic weighing techniques in terms of their suitability for very lean, very obese, and older individuals?

Suggested reading

1 Ellis KJ (2001) Selected body composition methods can be used in field studies. *Journal of Nutrition*, 131: 1589S–1595S.
This article provides an overview of the current status of in vivo *body composition methodologies that have potential for use in field-based studies. The methods discussed in this paper are*

divided into four general categories: anthropometric indices and skinfold, body volume measurements, body water measurements including bioelectrical methods, and imaging techniques.

2 Wang J, Thornton JC, Kolesnik S, Pierson RN Jr (2000) Anthropometry in body composition. An overview. *Annals of the New York Academy of Science*, 904: 317–326.
Anthropometry is a simple and reliable method for quantifying body size and proportions by measuring body length, width, circumference, and skinfold thickness. This article is an excellent resource for those interested in using anthropometric measurements to predict body composition.

Glossary

Air displacement plethysmography a body composition technique that is considered an alternative to hydrostatic weighing and uses air as opposed to water to determine body volume and thus body fat level.

Archimedes' principle the principle that relates buoyancy to displacement and states that weight loss under water is directly proportional to the weight of water displaced by the body.

Bioelectrical impedance analysis (BIA) a body composition technique that determines body fat levels by measuring impedance or opposition to the flow of an electric current.

Body composition the ratio of fat to fat-free mass and frequently expressed as a percentage of body fat.

Body density a measurement that expresses total body mass or weight relative to body volume or the amount of space or area that your body occupies.

Body mass index (BMI) also known as the Quetelet index calculated by dividing weight in kilograms by the square of height in meters.

Boyle's law this law states that at a constant temperature for a fixed mass, the product of pressure and volume of a gas is a constant and pressure and volume are inversely proportional.

Cellulite dimpled, quilt-like skin caused by fat being separated by connective tissue into small compartments that extrude into the dermis.

Circumference a body composition technique that determines body fat levels or distribution based on the circumference of selected body parts such as arms, legs, abdomen, and hips.

Densitometry the quantitative measurement of body composition that involves the determination of body density.

Dual-energy X-ray absorptiometry (DEXA) a body composition technique that uses a series of cross-sectional scans from head to toe using photon beams to determine body fat levels.

Ectomorph relative predominance of linearity and fragility with a large surface-to-mass ratio giving sensory exposure to the environment.

Endomorph relative predominance of soft roundness and large digestive viscera.

Essential fat the body fat stored in the bone marrow, heart, lungs, liver, spleen, kidneys, intestines, muscles, and lipid-rich tissues of the central nervous system.

Hydrostatic weighing a body composition technique that determines body volume by measuring the volume of water displaced by the body based on the Archimedes' principle that weight loss under water is directly proportional to the weight of water displaced by the body.

Mesomorph relative predominance of muscle, bone, and connective tissue ultimately derived from the mesodermal embroyonic layer.

Obese a condition where the BMI of an individual is higher than $30\,kg/m^2$.

Overweight a condition where the BMI of an individual is higher than $25\,kg/m^2$.

Resistance exercise performance of dynamic or static muscular contractions against external resistance of varying intensities.

Skinfold a body composition technique that determines body fat levels based upon the thickness of a double fold of skin and the immediate layer of subcutaneous fat.

Storage fat the body fat stored in adipose tissue and often referred to as a depot for excess fat.

Subcutaneous fat a portion of the storage fat found just beneath the skin's surface.

Visceral fat a portion of storage fat that protects the various organs within the thoracic and abdominal cavities.

15 Energy balance and weight control

Contents

Key terms

- Appetite
- Circuit weight training
- Excess post-exercise oxygen consumption
- Facultative thermogenesis
- Basal metabolic rate
- Duration
- Exercise
- Frequency

- Ghrelin
- Hypothalamus
- Intermittent exercise
- Negative energy balance
- Oxygen deficit
- Positive energy balance
- Set point
- Thermal effect of food
- High-intensity interval training
- Intensity
- Lactate threshold
- Obligatory thermogenesis
- Physical activity
- Resting metabolic rate
- Settling-point theory
- Weight cycling

How is body weight regulated?

In most people, body fat and weight remain remarkably constant over long periods despite fluctuations in food intake and activity level. It appears that when energy intake or activity level changes, the body compensates to prevent a significant change in body weight and fat. This is mainly because the body has the ability to balance energy intake and expenditure at a particular level or **set point**. For example, the body takes in an average of about 2500 kcal per day, or nearly one million kcal per year. However, the average gain of 0.7 kg (or 1.5 lb) of fat each year represents an imbalance of only 5250 kcal between energy intake and expenditure (3500 kcal is equivalent to 0.45 kg, or 1 lb, of adipose tissue). This translates into a surplus of fewer than 15 kcal per day.

Set point

According to the set-point theory, there is a control system built into every person dictating how much fat he or she should carry – a kind of thermostat for body fat. The set point for body fatness is determined by genetics. Some individuals have a high setting, others have a low one. In an obese individual, body fat is set to remain at a higher level than it is in a lean individual. When people lose weight, regardless of whether they are lean or obese, metabolic signals are generated to decrease energy output and increase energy intake in order to return their weight to its set point. According to this theory, body fat percentage and body weight are matters of internal controls that are set differently in different people.

The set-point theory has been well evidenced in both animal and human studies. When animals are fed or starved for various periods of time, their weights respectively increase or decrease markedly. But when they go back to their normal eating patterns, they always return to their original weight or to the weight of control animals. Similar results have been found in humans, although the number of studies is limited. Subjects placed on semi-starvation diets have lost up to 25 percent of their body weight but regained that weight within months of returning to a normal diet. It is the existence of a set point that makes weight loss a very difficult task, and most people who lose weight eventually regain all they have lost.

The set point that defends body weight is not always constant. Changes in physiological, psychological, and environmental circumstances do cause the level at which body weight is regulated to change, usually increasing over time. For example, body weight increases in most adults between 30 and 60 years of age, and, after having a baby, most women return to a weight that is 1 to 2 pounds higher than their pre-pregnancy weight.

Regulation of energy balance

The regulation of human energy balance is complex, involving numerous feedback loops to help control energy balance. The central nervous system, the brain in particular, is the

center for appetite control, either creating a sensation of satiety or stimulating food-seeking behavior. However, its activity is dependent upon a complex array of afferent signals from various body systems. The interaction of the brain with these afferent signals helps regulate the appetite on a short-term (daily) or on a long-term basis in order to keep the body weight constant. It is believed that signals related to food intake affect hunger or satiety over a short period of time, whereas signals from the adipose tissue trigger the brain to adjust both food intake and energy expenditure for long-term regulation.

Short-term regulation

The short-term regulation of energy balance involves the control of food intake from meal to meal. We eat in response to hunger, which is the physiological drive to consume food. We stop eating when we experience satiety, the feeling of fullness and satisfaction that follows food intake. What, when, and how much we eat are also affected by **appetite**, the drive to eat specific foods that is not necessarily related to hunger. Signals to eat or stop eating may be external, originating from the environment, or they may be internal, originating from the gastrointestinal tract, circulating nutrients, or high centers in the brain. The **hypothalamus** that lies in between the brain and brainstem contains neural centers that help regulate appetite and hunger. It is believed that the hypothalamus contains a hunger center that stimulates eating behaviors, and a satiety center that, once stimulated, inhibits the hunger center. As a means of controlling energy intake, specific neural receptors within the hypothalamus monitor various afferent stimuli that may augment or inhibit food intake.

The external signals that motivate eating include the sight, taste, and smell of food, the time of day, cultural and social conventions, the appeal of the foods available, and ethnic and religious rituals (Friedman 1995). As discussed in Chapter 7, sensory input such as the sight of a meal being presented on a table may cause your mouth to become moist and your stomach to begin to secrete digestive substances, and such a response may occur even when the body is not in need of food. Some people eat lunch at noon out of social convention, not because they are hungry. We eat turkey on Thanksgiving because it is a tradition, and we eat cookies and cinnamon rolls while walking through the mall because the smell entices us to buy them. Likewise, external factors such as religious dietary restrictions or negative experiences associated with certain foods can signal us to stop eating.

Internal signals that promote hunger and satiety are triggered after food is consumed and absorbed, thereby eliciting meal consumption or termination. The simplest type of signal about food intake comes from local nerves in the walls of the stomach and small intestine, which sense the volume or pressure of food and send a message to the brain to either start or stop food intake. When small amounts of food are consumed, the feeling of fullness associated with gastric stretching is barely noticeable. As the volume of food increases, stretch receptors are stimulated, relaying this information to the brain to cause the sensation of satiety.

The presence of food in the gastrointestinal tract also sends information directly to the brain and triggers the release of gastric hormones, the majority of which promote satiety (Woods *et al.* 1998). Of these satiety-promoting hormones, cholecystokinin or CCK is the best understood. As discussed in Chapter 7, this hormone is released from the intestinal cells, particularly in response to dietary fat and protein, signaling the brain to decrease food intake. The hormone that triggers hunger is **ghrelin** produced mainly by the stomach. Ghrelin is released in response to a lack of food, and circulating concentrations decrease after food is consumed. There is evidence that the over-production of ghrelin may contribute to obesity (Inui *et al.* 2004).

Absorbed nutrients may also send information to the brain to modulate food intake. Circulating levels of nutrients, including glucose, fatty acids, amino acids, and ketone, are monitored by the brain and may trigger signals to eat or not to eat. The pancreas is also involved in food intake regulation because it releases insulin, which may affect hunger and satiety by lowering the levels of circulating nutrients. The liver may also be involved in signaling hunger and satiety by monitoring changes in fuel metabolism. Changes in liver metabolism, in particular the amount of ATP, are believed to modulate food intake (Friedman 1995).

Long-term regulation

In addition to short-term regulation of food intake, the body also regulates energy intake on a long-term basis. Short-term regulators of energy balance affect the size and timing of individual meals. If a change in input is sustained over a long period, however, it can affect long-term energy balance and, hence, body weight and fatness. Long-term regulatory signals communicate the body's energy reserves to the brain, which in turn releases neuropeptides that influence energy intake and/or energy expenditure. If this long-term system functions effectively, body weight remains relatively stable over time.

The mechanisms that regulate long-term energy balance are complex and not well understood. However, the hormones leptin, and to a less extent, insulin, appear important (Figure 15.1). Leptin is produced primarily by adipose tissue, and when body fat increases, circulating leptin concentration increases as well. Likewise, when body fat decreases, leptin production decreases. Leptin travels in the blood to the hypothalamus where it binds to proteins called leptin receptors in order for the brain to release catabolic neuropeptides. Catabolic neuropeptides help the body resist further weight gain by decreasing energy intake and increasing energy expenditure. In this context, leptin acts like a thermostat to prevent body fatness from changing significantly.

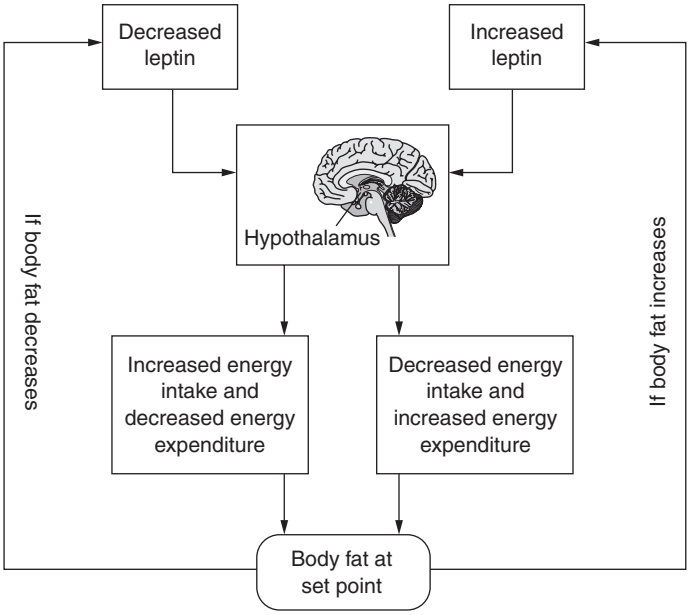


Figure 15.1 Operation of leptin in maintaining body fat at a set-point level

Along with leptin, the hormone insulin is also important in communicating adiposity to the brain. Insulin is secreted from the pancreas when blood glucose levels rise; its circulating concentration is proportional to the amount of body fat. Insulin can affect food intake and body weight by sending signals to the brain and by affecting the amount of leptin produced and secreted (Schwartz *et al.* 1999). When insulin levels are high, there will be a reduced drive for food as well as increased energy expenditure. As you may recall, insulin secretion increases after a meal. Such an acute rise in insulin acts as an anabolic hormone, favoring energy storage in peripheral tissues. Unlike insulin, acute changes in leptin are not easily detected after meals.

Overall, leptin and insulin are part of a more long-term homeostatic system that helps prevent large shifts in body weight. Some researchers believe that defects in the leptin/insulin signaling system may lead to impaired body weight regulation in some people (Cancello *et al.* 2004). In fact, many obese people are found to have high levels of both leptin and insulin, suggesting that these individuals may have developed tissue resistance to respond to these hormones. There is more to learn about this regulatory system. It seems clear that both leptin and insulin help protect the body during times of food scarcity. However, food regulation involving these two hormones may be altered or impaired during times of food surplus.

Components of daily energy expenditure

A healthy weight can result from paying more attention to the important concept of energy balance. Think of energy balance as an equation: energy input=energy output. While energy input refers to calories from food intake, energy output is accomplished by metabolism, digestion, absorption, transport of nutrients, and physical activity. When energy input is greater than energy output, the result is **positive energy balance**. The excess calories consumed are stored, which results in weight gain. There are some situations in which positive energy balance is normal and healthy. For example, during pregnancy, a surplus of calories supports the developing fetus. Infants and children require a positive energy balance for growth and development. On the other hand, if energy input is less than energy output, a **negative energy balance** is said to occur. A negative energy balance is necessary for successful weight loss. It is important to realize that during negative energy balance, weight loss involves a reduction in both lean and adipose tissue, not just fat. Thus far, issues related to energy intake have been discussed in previous chapters. This section focuses on the other side of the energy balance equation–energy output. The body uses energy for three general purposes: resting metabolism, physical activity, and digestion, absorption, and processing of ingested nutrients.

Resting metabolic rate

Resting metabolic rate (RMR) represents a minimal rate of metabolism necessary to sustain life. It is the energy requirements of a variety of cellular events that are essential to the life of an organism. RMR is typically measured three to four hours after a light meal without prior physical activity. Quantitatively, RMR accounts for about 60 to 75 percent of total daily energy expenditure. For this reason, this energy component has attracted a great deal of attention and has often been treated as a major player in contributing to metabolic disorders associated with energy imbalance. In many exercise intervention studies, RMR has been used as a major dependent variable expected to increase due to the exercise-induced increase in lean body mass. On an average of men and women combined, RMR has been estimated to be about 1680 $kcal \cdot day^{-1}$ for men and 1340 $kcal \cdot day^{-1}$ for women. RMR can simply be estimated by using the factor of one kcal

per kilogram body weight per hour. For example, for a male weighing 70 kg (154 lb), his daily RMR will be 1680 kcal (i.e., 1 kcal × 70 kg × 24 h). Such factors may be reduced from 1 to 0.9 kcal kg^{-1} hr^{-1} for use in women given that the average RMR is about 10 percent lower in women than in men. This method is convenient, but does not discriminate the age- or body composition-related differences. To eliminate this drawback, a revised equation was developed, which allows the estimation of RMR from fat-free mass (FFM) in kilograms (McArdle *et al.* 2001). The equation is expressed as follows:

$$\text{RMR} = 370 + 21.6\ (\text{FFM})$$

For example, a male who weighs 70 kg at 20 percent body fat has a FFM of 56 kg. By using the equation, his estimated daily BMR will be about 1580 kcal (i.e., $370 + 21.6 \times 56 = 370 + 1209.6 = 1579.6$). This equation was developed based on studies of a mixed sample of males and females and therefore should apply uniformly to both genders. The major advantage with this equation is that it takes into account the impact of body composition upon RMR and in doing so results can be more accurate in reflecting the gender- and age-related differences in metabolism despite the use of a single equation. This estimation approach, however, requires body composition to be measured in the first place, which could be problematic for those who don't have access to the body composition equipment.

RMR may also be estimated using the gender-specific Harris–Benedict equations (also called the Harris–Benedict principle), which provide an estimate for basal energy expenditure based on a subject's weight, height, and age. (Table 15.1). The questions were first developed in 1918 (Harris and Benedict 1918, 1919). In order to improve their accuracy they were revised in 1984 (Roza and Shizgal 1984) and in 1990 (Mifflin *et al.* 1990) (Table 15.1). Note that the equations estimate **basal metabolic rate** (BMR) rather than resting metabolic rate. BMR is more precisely defined as the energy expenditure measured immediately after awakening in the morning. BMR measurements are typically taken in a darkened room upon waking after 8 hours of sleep, 12 hours of fasting to ensure that the digestive system is inactive, and with the subject resting in a reclined position. In practice, RMR and BMR differ by less than 10 percent, so the terms may be used interchangeably.

RMR may be affected by body weight and composition. As shown in Table 15.2, this energy component may also be influenced by many other factors such as age, climate, and hormones. As compared to adults, infants have a large proportion of metabolically active tissue. Hence, their mass-specific RMR is higher than that of adults. However, RMR declines through childhood, adolescence, and adulthood as full growth and maturation are achieved. Mass-specific RMR will show a continued decline in those who become elderly (i.e., who reach or pass the age of 65). This is because aging has been

Table 15.1 Original and revised Harris–Benedict equations

The original Harris–Benedict equations published in 1918 and 1919	
Men	BMR = 66.5 + (13.75 × weight in kg) + (5.003 × height in cm) – (6.755 × age in years)
Women	BMR = 655.1 + (9.563 × weight in kg) + (1.850 × height in cm) – (4.676 × age in years)
The Harris–Benedict equations revised by Roza and Shizgal in 1984	
Men	BMR = 88.362 + (13.397 × weight in kg) + (4.799 × height in cm) – (5.677 × age in years)
Women	BMR = 447.593 + (9.247 × weight in kg) + (3.098 × height in cm) – (4.330 × age in years)
The Harris–Benedict equations revised by Mifflin and St Jeor in 1990	
Men	BMR = (10 × weight in kg) + (6.25 × height in cm) – (5 × age in years) + 5
Women	BMR = (10 × weight in kg) + (6.25 × height in cm) – (5 × age in years) – 161

Table 15.2 Factors that affect resting metabolic rate (RMR)

Factors	*Effect*
Body size	An increase in body size increases RMR
Body composition	An increase in lean body mass increases RMR
Growth	Mass-specific RMR declines through childhood, adolescence, and adulthood
Age	Mass-specific RMR continues to decline from adulthood into elderly
Ambient temperature	Both cold and warm exposure will stimulate RMR
Hormones	Both thyroid hormone and epinephrine will stimulate RMR
Aerobic fitness	A high level of aerobic fitness is linked to an increased RMR
Resistance training	Resistance training increases RMR or prevents a decline in RMR as one ages
Smoking	Nicotine increases RMR
Caffeine	Caffeine stimulates RMR
Sleeping	RMR decreases during period of sleeping
Nutritional status	Underfeeding tends to reduce RMR, while overfeeding tends to increase RMR

associated with the loss of lean body mass, which includes muscle as well as other metabolically active organs. Climate conditions, especially temperature changes, can also raise resting energy expenditure. For example, exposure to the cold may stimulate muscle shivering as well as the secretion of several thermogenic hormones such as epinephrine and thyroid hormone. Exposure to a warm environment will also provoke an increase in energy metabolism, although this increase may not be as great in magnitude as that induced in a cold environment. RMR is also subject to the change in hormonal concentration. The two major hormones linked to RMR are epinephrine and thyroid hormone.

Physical activity

Physical activity is a powerful metabolic stressor. It stimulates chemical processes in which the potential energy stored in energy substrates is converted into the type of energy that cells can utilize, namely ATP. As mentioned in Chapter 9, in an aerobic event, energy utilization associated with a particular exercise may be quantified by determining the amount of oxygen used, with oxygen being later converted into calories. Determination of energy cost for an anaerobic event is much more complex and may be achieved via measurement of production of muscular force and power, utilization of energy substrates (i.e., ATP, PCr, glucose), or energy utilization following the completion of exercise. Knowing the energy cost of exercise is important if a comparable nutritional requirement needs to be provided or if the efficiency of the body during performance of exercise is to be calculated.

The total energy cost for a given activity should be assessed both during and following exercise. This is especially the case when exercise is performed at high intensities that require a longer recovery period. During exercise, there is an increase in VO_2 to support the increased energy needs of the body. However, the body's ability to gauge such a demand for oxygen is not always perfect. At the onset of exercise, both respiration and circulation do not immediately supply the needed quantity of oxygen to the exercising muscle (Figure 15.2). Oxygen supply normally requires several minutes to reach the required level at which aerobic processes are fully functional. The difference in oxygen requirement and oxygen supply is regarded as **oxygen deficit**. After exercise VO_2 does not return to resting

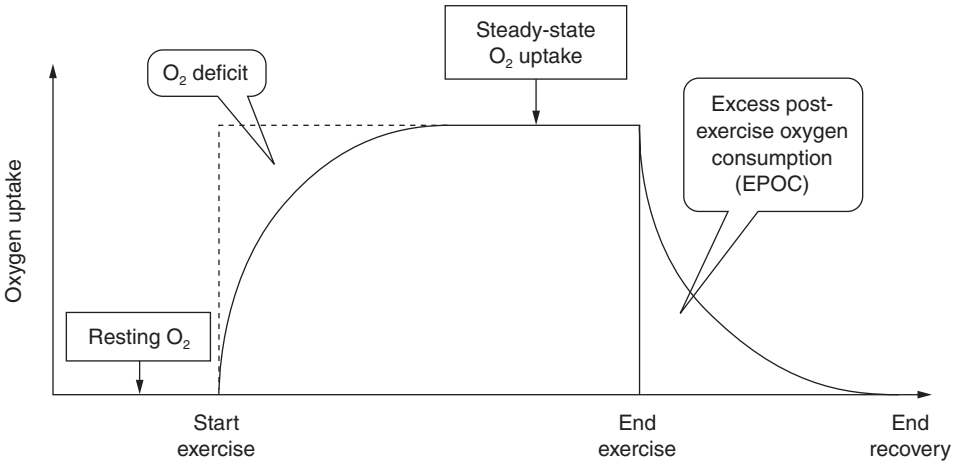


Figure 15.2 Response of oxygen uptake during steady-state exercise and recovery

levels immediately but does so gradually. This elevated oxygen consumption following exercise has been referred to as **excess post-exercise oxygen consumption** (EPOC). The current theory of EPOC reflects two factors: (1) the level of anaerobic metabolism in previous exercise, and (2) the exercise-induced adjustments in respiratory, circulatory, hormonal, and thermal function that still exert their influences during recovery.

Understanding the dynamics of EPOC enables us to more adequately quantify the energy cost of an activity, especially when the activity performed is intense and brief, such as sprinting or resistance exercise. Due to their anaerobic nature, these strenuous and short-duration work bouts could drastically disturb the body's homeostasis throughout exercise which demands a greater level of oxygen consumption during recovery. As such, these types of exercise are often associated with a fairly large EPOC that may constitute a majority of the total energy associated with exercise. The phenomenon of EPOC has also been brought to attention in the area of weight management due to its role in facilitating energy expenditure. Overweight or obesity is the result of a positive energy balance and EPOC can contribute to the opposite extreme when exercise is undertaken regularly. Nevertheless, it has been suggested that in order for EPOC to be effective, one would have to exercise at an intensity exceeding 70 percent VO_2max for more than an hour, three times a week (Borsheim 2003). Apparently, this volume of exercise is often impractical for many overweight or obese individuals.

Walking and running are the two principle forms of human locomotion. From an energetic point of view, walking is an energy-cheap activity, and its energy cost is generally no more than three times the resting metabolic rate. On the other hand, running can be very demanding metabolically, as it engages more muscles that contract forcefully. On an average, the energy expenditure during running can reach as high as ten times the resting metabolic rate (Table 15.3).

Cycling is the major means of transportation in many countries of the world. This form of exercise is also used as a recreational and competitive sport. During the past decade or so, off-road cycling has enjoyed an exponential growth in popularity. In the fitness and rehabilitation industry, cycling is often performed on a stationary ergometer, which allows exercise intensity to be regulated. Stationary cycling differs from outdoor cycling in that it provides a broad range of exercise intensities that can be adjusted by

Table 15.3 Energy expenditure during various physical activities

Activity	*Energy expenditure (kcal·min^{-1})*	
	Men	*Women*
Sitting	1.7	1.3
Standing	1.8	1.4
Sleeping	1.2	0.9
Walking (3.5 mi h^{-1}, 5.6 km h^{-1})	5.0	3.9
Running (7.5 mi h^{-1}, 12.0 km h^{-1})	14.0	11.0
Running (10.0 mi h^{-1}, 16.0 km h^{-1})	18.2	14.3
Cycling (7.0 mi h^{-1}, 11.2 km h^{-1})	5.0	3.9
Cycling (10.0 mi h^{-1}, 16.0 km h^{-1})	7.5	5.9
Weight-lifting	8.2	6.4
Swimming (3.0 mi h^{-1}, 4.8 km h^{-1})	20.0	15.7
Basketball	8.6	6.8
Handball	11.0	8.6
Tennis	7.1	5.5
Wrestling	13.1	10.3

Source: adapted from Wilmore and Costill (2004).

manipulating either pedal speed or flywheel resistance. Cycling uses less muscle mass as compared to running, and as a result expends less energy (Table 15.3). However, the non-weight-bearing feature of this activity allows cycling to be more tolerable for and commonly chosen by those who are extremely sedentary and/or obese or those who have difficulty performing weight-bearing activities.

Resistance exercise or weight-lifting has been widely used in various sports training programs as well as in health and fitness-related exercise interventions. Every activity, including activities of daily living, requires a certain percentage of an individual's maximum strength and endurance. Regular resistance exercise can serve as a potent stimulus to the musculoskeletal system that is necessary to bring about the gain in muscle size and function. It also helps in enhancing bone mass and the strength of connective tissue. A training routine that combines both aerobic and resistance exercises has been highly recommended because the resulting improvement in cardiorespiratory and muscular function can allow individuals to not only reduce their risks for chronic diseases related to physical inactivity, but also to be able to perform activities of daily living comfortably and safely.

Less information is available concerning the energy cost of resistance exercise. This may be due to the fact that this type of exercise is typically performed in an intermittent fashion so that the accumulated exercise time is relatively short. Although exertion can be quite strenuous at times during resistance exercise, these moments of strenuous phases are usually not sustained for more than one minute. Table 15.4 provides results of net VO_2 from studies that have examined the energy cost of resistance exercises (Halton *et al.* 1999, Hunter *et al.* 1988, 1992, Olds and Abernethy 1993, Willoughby 1991, Wilmore *et al.* 1978). It appears that a greater energy cost is produced during a **circuit weight training** routine that involves multiple sets of low intensity (i.e., 40 percent 1-RM) and high repetitions (i.e., 10 to 15 repetitions) on each muscle group, coupled with a relatively shorter rest interval between sets (i.e., ~15 seconds). Energy cost during resistance exercise has also been reported using gross VO_2 for which the resting component is not subtracted from the total value (Burleson *et al.* 1998, Phillips and Ziuraitis 2003). With this approach, VO_2 was found to be near 1 to 1.5 l min^{-1}, a range that is generally

higher compared to those in Table 15.4. When the total oxygen consumed is accumulated over an entire exercise session, it ranges from 30 to 451·session^{-1} or 150 to 225 kcal·session^{-1}. This level of oxygen uptake is considered mild given that the gross caloric expenditure is capable of reaching 400 to 500 kcal during a typical endurance exercise of moderate intensity that lasts for ~45 minutes.

Although it may not accumulate as much energy expended while exercising, resistance exercise can disturb the body's homeostasis to a greater extent as compared with aerobic exercise. The physiological strain it imposes may persist through a sustained period of recovery following exercise. As such, resistance exercise is often associated with a greater EPOC than aerobic exercise. For example, Burleson *et al.* (1998) found a greater EPOC following circuit weight training performed at 60 percent 1-RM as compared to treadmill exercise that was matched for the same VO_2 elicited during resistance exercise. The greater EPOC is attributable to the fact that a majority of the energy that supports the activity is derived from the use of anaerobic energy sources such as ATP and CP, which requires oxygen for them to be replenished following exercise. It may also be due to a greater change in HR as well as concentration of blood lactate and selected hormones imposed during exercise that will cause a sustained elevation in oxygen consumption following exercise. Many studies have examined the effect of resistance exercise on EPOC (Binzen *et al.* 2001, Kang *et al.* 2005b, Thornton *et al.* 2002, Melby *et al.* 1993, Melanson *et al.* 2002, Olds and Abernethy 1993, Schuenke *et al.* 2002). It is generally agreed that although the lifting mode and intensity (i.e., % 1-RM) can be influential, it is the volume of resistance training, which represents the total quantity of weights lifted, that serves as the most important factor to determine the magnitude of EPOC. Using the respiratory exchange ratio, several studies also revealed a greater fat utilization in addition to the greater EPOC following resistance exercise (Binzen *et al.* 2001, Melby *et al.* 1993).

Table 15.4 Comparisons of studies that have examined energy cost of resistance exercise

Studies	*Subjects*	*Volume/intensity*	*VO_2 ($l\ min^{-1}$)**
Willoughby *et al.* (1991)	10 men	Squat at 50% 1-RM, 7 reps	0.18
		Squat at 70% 1-RM, 6 reps	0.19
		Squat at 90% 1-RM, 5 reps	0.24
Halton *et al.* (1999)	7 men	1 circuit of 8 exercises at 75% 20-RM, 20 reps	0.29
Olds and Abernethy (1993)	7 men	2 circuits of 7 exercises at 60%, 15 rep	0.78
		2 circuits of 7 exercises at 75%, 12 rep	0.78
Hunter *et al.* (1988)	10 men	4 sets of bench press at 20% 1-RM, 30 reps	0.14
	7 women	4 sets of bench press at 40% 1-RM, 20 reps	0.23
		4 sets of bench press at 60% 1-RM, 10 reps	0.30
		4 sets of bench press at 80% 1-RM, 5 reps	0.51
Wilmore *et al.* (1978)	20 men	3 circuits of 10 exercises at 40% 1-RM,	1.00
	20 women	15–18 reps	
Hunter *et al.* (1992)	14 men	4 sets of knee extension at 60% 1-RM, 10 reps	0.46
	8 women	4 sets of knee extension at 80% 1-RM, 5 reps	0.48
		4 sets of knee flexion at 60% 1-RM, 10 rep	0.58
		4 sets of knee flexion at 80% 1-RM, 5 reps	0.60

Notes

* Values are the net VO_2 averaged over exercise and recovery periods. Net VO_2 is computed as exercise VO_2 + recovery VO_2 – resting VO_2 accumulated for the total period of exercise and recovery.

Thermal effect of foods

Diet induced thermogenesis or the **thermal effect of foods** (TEF) represents another important component of total daily energy expenditure. This energy fraction is defined as the significant elevation of the metabolic rate that occurs after ingestion of a meal. Typically, this elevation reaches its peak within an hour and can last for four hours in duration after a meal. TEF is proportional to the amount of energy being consumed and is estimated at about 10 percent of energy intake. For example, an individual consuming 2000 kcal probably expends about 200 kcal on TEF.

TEF may be divided into two subcomponents: **obligatory thermogenesis** and **facultative thermogenesis**. The obligatory component of TEF is the energy cost associated with digestion, absorption, transport, and assimilation of nutrients as well as the synthesis of protein, fat, and carbohydrate to be stored in the body. The facultative thermogenesis is thought to be mediated by the activation of the sympathetic nervous system, which functions to stimulate metabolic rate. This classification in essence provides underlying mechanisms that explain the increment in thermogenesis following a meal.

TEF can be different depending on whether protein, carbohydrate, or fat is being consumed. It is widely accepted that the TEF produced by protein is about 20 to 30 percent of the energy intake, whereas TEF for carbohydrate and fat approximates 5 to 10 and 0 to 5 percent, respectively. This relationship may be attributed to the differences in chemical structure of these nutrients, which dictate the amount of energy that is necessary for them to be digested, absorbed, assimilated, and stored. Consumption of protein is considered most thermogenic partly because protein contains nitrogen that needs to be removed, which is energy costly. In addition, most amino acids are absorbed by an energy-requiring process. Absorbed amino acids may also be used for protein synthesis. In this process, energy is mainly used for synthesizing peptide bonds.

The relatively large calorigenic effect of ingested protein has been used as evidence to promote a high-protein diet for weight loss. This is based on the belief that as a greater amount of energy is needed during the process in which protein is digested, absorbed, and assimilated, fewer calories will become available to the body for storage as compared to a meal consisting mainly of carbohydrate and fat. However, this notion needs to be viewed with caution in that it has been claimed that a high-protein intake can lead to hypoglycemia and protein degradation as well as harmful strain on the kidneys and liver in the long run.

Etiology of obesity

Obesity is defined as an excess accumulation of body fat (i.e., body mass index $\geq 30\,kg\,m^2$). It refers to the overfat condition that is associated with a number of comorbidities including: glucose intolerance, insulin resistance, dyslipidemia, non-insulin-dependent (or type 2) diabetes, hypertension, and increased risk of coronary heart disease and cancer. Obesity may be simply attributed to energy imbalance in which energy intake chronically exceeds energy expenditure. Disruption in energy balance often begins in childhood, and those who are overweight in their childhood will have a significantly greater chance of becoming obese adults as well. Childhood obesity has been in part ascribed to parental obesity. For example, if parental obesity also exists, the child's risk of obesity in adulthood is two to three times that of normal-weight children without obese parents. The ages of 25 to 45 years represent another dangerous period in which there is a progressive weight gain over time (Crawford *et al.* 2000). There are reports indicating that despite a progressive decrease in food consumption, a 35-year-old male will gain an average of 0.5 kg (or 1 lb) of fat each year until the sixth decade of life.

In simple terms, obesity is caused by a positive energy balance, which is when energy intake is greater than energy output. Although a positive energy balance provides the basic answer to how we get fat, it does not provide any insight relative to the specific mechanisms. It remains unclear as to whether obesity results from alterations in lifestyle or reflects a normal biological pattern. Claude Bouchard, a prominent international authority on obesity and weight control, noted that currently there is no common agreement on the specific determinants of obesity, emphasizing that numerous factors are correlated with body fat content. In general, most leading scientists support a multicausal theory involving the interaction of a number of genetic and environmental factors.

Heredity

Experimental studies on animals have linked obesity to hereditary (genetic) factors. Research on humans has also shown a direct genetic influence on height, weight, and BMI. Most human studies used monozygotic (identical, developed from one embryo) and dizygotic (non-identical, developed from two separate embryos) twins to examine environmental and genetic influences on the development of obesity. Perhaps a study from Laval University in Quebec provided the strongest evidence of a significant genetic component of obesity (Bouchard *et al.* 1990). The investigators took 12 pairs of young adult male monozygotic (identical) twins and housed them in a closed section of a dormitory under 24-hour observation for 120 consecutive days. The subjects' diets were monitored during the initial 14 days to determine their baseline caloric intake. Over the next 100 days, the subjects were fed 1000 kcal above their baseline consumption for 6 out of every 7 days. On the seventh day, the subjects were fed only their baseline diet. Thus, they were overfed in 84 out of 100 days. Activity levels were also tightly controlled. At the end of the study period, the actual weight gained varied widely from 4.3 to 13.3 kg (9.5 to 29.3 lb) despite an overconsumption of the same calories. However, the response of both twins in any given twin pairs was quite similar. Similar results were found for gains in fat mass, percentage of body fat, and subcutaneous fat.

Research into the genetics of obesity has been progressing at a rapid pace. To date, several obesity genes have been identified, which may explain why some individuals maintain an unhealthy set point. It is generally considered that individuals with a genetic susceptibility to obesity may be predisposed to abnormalities in neural function. These individuals establish neural circuits that are not easily abolished. In essence, obesity genes influence appetite to increase energy intake or affect metabolism to decrease energy expenditure. For example, genes in the hypothalamus may decrease the number of protein receptors for leptin, thus preventing leptin from inhibiting the appetite.

Many studies have also pointed out a potential role which uncoupling proteins (UCPs) play in the etiology of obesity. As noted in Chapter 8, UCPs function to activate thermogenesis. Several forms of UCPs have been identified, i.e., UCP1 in brown fat tissue, UCP2 in white fat and muscle tissue, and UPC3 in muscle tissue (Lowell and Spiegelman 2000). It has been evidenced that these uncoupling proteins were underexpressed in tissues of obese individuals, and the lower the UPCs, the lower the resting metabolic rate. To date, more than 300 genes are considered to be involved in weight loss and weight maintenance. Genetic factors that have been implicated in the development of obesity include: (1) a predisposition to sweet and high-fat foods; (2) an inability to control appetite; (3) impaired functions of hormones such as insulin and leptin; (4) reduced levels of human growth hormones; (5) decreased resting energy expenditure; (6) reduced rates of fat oxidation, and (7) an enhanced efficiency in storing fat and conserving energy.

Environmental factors

Heredity may predispose one to obesity. However, environmental factors are also highly involved. Some would argue that body weight similarities among family members stem more from learned behaviors rather than genetic similarities. Even married couples, who have no genetic link, may behave similarly toward food and eventually assume similar degrees of leanness or fatness. Proponents of nurture pose that environmental factors, such as a high-calorie or fat diet and inactivity, literally shape us. This notion seems likely when considering that our gene pool has not changed much in the past 50 years, whereas according to the US Centers for Disease Control the prevalence of obesity has grown in epidemic proportions over the past two decades.

Factors related to energy consumption

Although excess calories, or overfeeding, may lead to weight gain and obesity, researchers suggest that the main "culprit" in the diet that leads to obesity is dietary fat. Researchers have postulated several reasons for why dietary fat plays a major role in causing weight gain and obesity. Dietary fat is highly palatable to most individuals, encouraging overconsumption. Dietary fat contains more calories per gram, and may not provide the same satiety as carbohydrate and protein. It has been demonstrated that high-fat foods give rise to higher energy intake during a meal than do carbohydrate and protein, and calories for calories are less effective in suppressing subsequent food intake (Green and Blundell 1996). Spontaneous energy intake is also higher on an unrestricted high-fat diet compared to a high-carbohydrate diet (Shah and Garg 1996). Dietary fat may be stored as fat more efficiently compared to carbohydrate and protein. It takes some energy to synthesize fat and store it in adipose tissue, but in comparison to dietary fat, it may cost up to three to four times more energy to convert carbohydrate or protein into body fat. In addition, it has been found that chronic intake of a high-fat diet will produce resistance in the hypothalamus to various factors that normally suppress appetite, such as leptin, resulting an increased energy intake and body fat deposition (Tso and Liu 2004).

From an energy balance perspective, obesity may also be attributed to an increased daily caloric intake regardless of its composition. Our society promotes increased food intake. Supermarkets, fast-food restaurants, and all-night convenience stores provide ready access to food throughout the day and night. Appetizing low-fat but high-calorie food is everywhere, and in supersize proportions which significantly increase caloric content. Bigger is marketed as better in terms of portion size. People buy large sizes and combinations, perceiving them to be good value, but then they eat more than what they need. What was once small is now large. For example, the average soft drink is over 50 percent larger compared to what it was before and some of which may contain over 500 calories. The trend toward large portion sizes parallels the prevalence of overweight and obesity, beginning in the 1970s, increasing sharply in the 1980s, and continuing today.

With excess dietary calories, it is possible for an individual to become obese even on a low-fat diet because the body rapidly adjusts to oxidizing excess dietary carbohydrate and protein to meet its energy needs, sparing the use of body fat stores. In addition, some of the excess dietary carbohydrate may also be used to generate body fat. Recent research by Ma *et al.* (2005) indicates that a high glycemic index diet is associated with increased body weight. This evidence suggests that weight gain may occur without a necessary increase in fat consumption.

Factors related to energy expenditure

As mentioned earlier, the total energy expenditure may be partitioned into energy expended via (1) resting metabolic rate, (2) thermal effect of food, and (3) physical activities. Of these three energy components, both the resting metabolic rate and energy cost due to physical activity appear to receive the most attention in terms of studying the etiology of obesity. This may be because thermogenesis associated with food consumption constitutes a very small portion of the daily energy expenditure. Resting metabolism is the energy required by the body in a resting state. It may be influenced by age, gender, drugs, climate, body weight, and body composition, and accounts for a majority of daily energy expenditure. There is a gradual decline in resting metabolism as one ages. In addition, those with greater lean body mass will have greater resting metabolism. However, as related to obesity, several studies have failed to prove that this energy component is responsible for obesity. For example, Seidell *et al.* (1992) and Weinsier *et al.* (1995) reported that a gain in body weight occurred independent of changes in resting metabolism over ten and four years, respectively. In fact, obese individuals were found to have an expended lean body mass and thus greater resting metabolic rate (Bray 1983).

Obesity may also be explained by concomitantly decreasing levels of physical activity. Energy output associated with physical activity can vary tremendously. As such, this energy component has been the center of a majority of research dealing with obesity and its prevention and treatment. Despite some controversy, there has been a popular belief that a reduced level of physical activity leads to the development of obesity (Astrup *et al.* 2002). Modern technology is helping to make our lives more comfortable and enjoyable in numerous ways. However, technology may also exert a negative effect on our health as the development of television, computers, and other labor-saving devices may decrease levels of physical activity. Indeed, both longitudinal and cross-sectional studies have reported an inverse relationship between physical activity and body weight; that is, those who were physically inactive weighed more. Once an individual becomes obese, physical activity decreases, setting up a vicious cycle of increasing body weight and then less physical activity.

It should be noted, however, that those who are obese tend to expend relatively more energy for any given movement (Bray 1983). Consequently, despite reduced physical activity, the resulting energy expenditure may not necessarily be less in obese as compared with lean individuals. This raises a question as to whether or to what extent a decrease in physical activity actually contributes to the occurrence of obesity. It has been recently suggested that the impact of energy expenditure upon the cause of obesity can vary from individual to individual and can also have different effects within individuals at different stages of development. Perhaps future studies aimed at the etiology of obesity should be devoted to examining the impact of energy balance over time using relatively homogeneous groups in terms of age, gender, fitness, and severity of obesity.

Interactions of heredity and environment

It is unlikely that the increasing incidence of obesity in the US is due to genetics only because it takes many generations to change the genes present in a population. Therefore, non-genetic factors such as increased energy intake and decreased physical activity are thought to be major contributors to our increasing body weight. When genetically susceptible individuals find themselves in an environment where food is appealing and plentiful and physical activity is easily avoided, obesity is a likely outcome. An example of human obesity that is due to the interaction of a genetic predisposition and an environment that is conducive to obesity is the Pima Indian tribe living in Arizona. More than

75 percent of this population is obese. Several genes have been identified and considered responsible for this group's tendency to store more fat (Norman *et al.* 1997). Typically, Pimas have low energy requirements per unit of fat-free mass, which, coupled with a low level of physical activity and a high intake of energy-dense diet, has caused body fat to be maintained at a high level. A group of Pima Indians living in Mexico are genetically the same as those in the US, but they are farmers who consume the food they grow and have a high level of physical activity (Esparza *et al.* 2000). They still have higher rates of obesity than would be predicted from their diet and exercise patterns, suggesting genes that favor high body weight. However, they are significantly less obese than the Arizona Pima Indians.

The interaction of heredity and environment may also explain why some people attain and maintain body weights higher than their set point. It is now believed that an individual's set point is adjustable, possibly shifting with changes in the hypothalamus. Some scientists have proposed a new theory, the settling-point theory. The **settling-point theory** suggests that the set point may be modified, and in the case of weight gain, set at a higher level. In other words, whatever genes we have that make us susceptible to obesity may settle into a happy equilibrium with our environment. For example, a chronically high-fat diet may modify our genes, possibly increasing leptin resistance, and body weight rises to a new level. On the other hand, a weight loss diet may lower the set point to help maintain body weight at a lower level. Weinsier *et al.* (2000) found that caloric restriction in obese women induced a transient decrease in resting energy expenditure, which would be counterproductive to weight loss. However, metabolism returned to normal on completion of a weight loss program when energy intake was then adequate to maintain the reduced body weight, suggesting that the set point may settle to a lower level over time. Clearly, genetics and environment interact to influence body weight and composition.

Dietary therapies designed to reduce energy intake

Although the weight loss industry would like us to think otherwise, the truth is clear: there is no quick and easy way to lose weight. Treatment of overweight and obesity should be long term, similar to that for any chronic disease. It requires a firm commitment to lifestyle changes, rather than a quick fix as promoted by many popular diet books. We often view a diet as something one goes on temporarily, only to resume prior (typically poor) habits once satisfactory results have been achieved. This is why so many people regain lost weight. Instead, an emphasis on healthy, active living with acceptable dietary modifications will promote weight loss and later weight maintenance.

Weight loss guidelines and approaches

Although there are many reasons why people want to lose weight, the most important one is to improve health. Rather than focusing on weight loss, which is unlikely to be successful in the long term, a weight problem should be viewed in terms of weight management. One goal of weight management is to prevent excess body weight gain. Healthy eating habits and active lives that promote the maintenance of a healthy weight should be developed in childhood and maintained throughout life. Just as dietary and lifestyle changes which people adopt in response to a family history of heart disease or an increase in blood cholesterol, similar actions should be taken as well to maintain a healthy weight if someone is exposed to a family history of obesity or an increase in body weight. For those who are already overweight, the goal of weight management is to reduce body weight and body fat to a healthy level that can be maintained over a lifetime.

Achieving and maintaining weight loss requires making lasting lifestyle changes, including what we choose to eat and how much physical activity we engage in. Most health experts suggest that people focus less on weight loss and more on eating healthily and on overall fitness. Misguided efforts of weight loss at any cost unfortunately present food as the enemy, rather than as means to good health. Most people who successfully lose weight and keep it off do so by eating a balanced diet of nutrient-dense foods and by maintaining a moderately high level of physical activity (Wing and Phelan 2005). A healthy weight loss and weight maintenance program consists of four components: (1) setting reasonable goals; (2) choosing foods sensibly; (3) increasing physical activity, and (4) modifying behavior. These are described as follows.

Setting reasonable goals

Setting reasonable and attainable goals is an important component of any successful weight management program. For most people, a loss of 5 to15 percent of body weight, most of which is fat, will significantly reduce disease risk. Therefore, it has been suggested that the initial goal of weight loss should be to reduce body weight by approximately 10 percent over a period of about six months (National Institute of Health; National Heart, Lung, and Blood Institute 1998). A gradual loss of 10 percent of body weight is considered achievable for most individuals and is easier to maintain than larger weight losses. Most people who lose large amounts of weight or lose weight rapidly eventually regain all that they have lost. Repeated cycles of weight loss and regain, often referred to as **weight cycling**, may increase the proportion of body fat with each successive weight regain and cause a decrease in RMR, making subsequent weight loss more difficult (Seagle *et al.* 2009).

When it comes to weight loss, slow and steady is the way to go, and weight loss should not exceed one to two pounds a week. This will promote the loss of fat and not lean tissue. It is estimated that a pound of fat provides 3500 kcal. Therefore, to lose a pound of fat, one must decrease energy intake and/or increase energy output by this amount. To lose a pound a week, one must shift energy balance by 500 kcal per day (3500 kcal ÷ 7 days = 500 kcal/day). Note that this is the predicted average weight loss at this energy deficit. The actual amount of weight loss per week may vary over time. Rather than making dramatic dietary changes, small changes such as reducing portion sizes and cutting back on energy-dense snacks make a big difference in overall energy intake. Once body weight stabilizes and the new lower weight is maintained for a few months, a decision can be made whether additional weight loss is needed.

Table 15.5 outlines the recommendations of a weight loss diet made by the National Institutes of Health Obesity Education Initiative (2000). What is reflected in the recommendations is that energy intake should provide nutritional adequacy without excess; that is, somewhere between deprivation and complete freedom to eat. A reasonable suggestion is that an adult needs to increase activity levels and reduce food intake sufficiently to create a deficit of 500 kcal per day. As mentioned earlier, such a deficit produces a weight loss of about one pound a week, a rate that supports the loss fat efficiently, while retaining lean tissue. In general, weight loss diets provide 1200 to 1600 kcal a day.

Choosing foods sensibly

Contrary to the claims of fad diets, no one food plan is magical and no specific food should be included or avoided in a weight management program. In fact, weight loss plans that drastically reduce calories and offer limited food choices leave people feeling hungry and dissatisfied. Thus, weight loss diets that encourage people to eat foods that are healthy and appealing tend to have greater success.

Table 15.5 General recommendations for a weight loss diet

Nutrient	*Recommended intake*
Kcal (BMI ≥35)	500–1000 kcal per day reduction from usual intake
Kcal (BMI between 27 and 35)	300–500 kcal per day reduction from usual intake
Total fat	30% or less of total kcal
Saturated fatty acids	8–10% of total kcal
Monounsaturated fatty acids	Up to 15% of total kcal
Polyunsaturated fatty acids	Up to 10% of total kcal
Cholesterol	300 mg or less per day
Protein[a]	Approximately 15% of total kcal
Carbohydrate[b]	55% or more of total kcal
Sodium chloride	No more than 2400 mg of sodium or approximately 6 g of sodium chloride (salt) per day
Calcium	1000 to 1500 mg per day
Fiber	20 to 30 g per day

Source: National Institutes of Health Obesity Education Initiative (2000).

Notes
a Protein should be derived from plant sources and lean sources of animal protein.
b Carbohydrate and fiber should be derived from vegetables, fruits, and wholegrains.

The main characteristic of a weight loss diet is that it provides less energy than the person needs to maintain current body weight. Reducing energy intake is best achieved by cutting back on energy-dense foods that have little nutritional value such as soft drinks, potato chips, cookies, and cakes. Aside from their low-energy densities, foods such as wholegrains, legumes, nuts, fruits, and vegetables offer many health benefits such as micronutrients and fiber. In addition, these foods tend to have greater volume compared to more energy-dense foods, thus helping people feel full more easily.

Most people still believe that to lose weight one should avoid foods that contain fat. However, this is not the case. As discussed in Chapter 10, the *Dietary Guidelines for Americans* now recommend that we choose our fats as carefully as we choose our carbohydrates. In general, it is best to limit intake of foods containing trans and saturated fatty acids. Foods containing relatively more polyunsaturated and monounsaturated fatty acids are healthier. Another common misconception is that dairy products and meat are high-fat foods that should be avoided when trying to lose weight. Again, the key to good nutrition is moderation and choosing wisely. For example, switching from whole- to reduced-fat milk is one way to lower caloric intake without losing many vitamins and minerals found in dairy products. Likewise, how meat is prepared and what types of meat are consumed can greatly affect the amount of calories consumed. Lean meats prepared by broiling or grilling are both nutritious and satisfying.

Healthy eating also requires people to pay attention to hunger and satiety cues. Rather, the amount of food served or packaged often determines how much we eat. That is, visual cues, rather than internal cues, have a greater influence on the quantity of food consumed. For example, some commercially made muffins are extremely large, containing as many calories as eight slices of bread. Therefore, learning to choose reasonable portions of food is a critical component to successful weight management. In fact, reducing portion sizes by as little as 10 to 15 percent could reduce our daily caloric

intake by as much as 300 kcal. One way to limit serving size is to consider sharing large and supersize meals the next time you eat in a restaurant.

Table 15.6 presents some examples of how to save kcal via simple substitutions. By choosing foods wisely, a significant reduction in fat and total calories may be achieved. As you should realize, it is best to consider eating healthily and making a lifestyle change rather than a weight loss plan. A person who adopts a lifelong "eating plan for good health" rather than a "diet for weight loss" will be more likely to keep the lost weight off. Keep in mind that well-balanced diets that emphasize fruits, vegetables, wholegrains, lean meats or meat alternatives, and low-fat milk products offer many health benefits even when they don't result in weight loss.

Increasing physical activity

Physical activity is an important component of any well-designed weight management program. Exercise promotes fat loss and weight maintenance. It increases energy expenditure, so if intake remains the same, energy stored as fat is used as fuel. In theory, an increase in activity of 200 kcal five times a week will result in the loss of a pound of fat in about three and a half weeks. Exercise also promotes muscle development. This is important during weight loss because muscle is metabolically active tissue. Increase in muscle mass helps prevent the decrease in resting metabolic rate that occurs as body weight decreases. Weight loss is also better maintained when physical activity is included in the weight management program (Wilmore 1996).

It is important to realize that people can be physically fit while being overweight. Normal blood pressure and healthy blood glucose concentration and lipid profile are important indicators of physical fitness. Studies show that obese individuals who are physically fit have fewer health problems than do average-weight individuals who are unfit (Lovejoy *et al.* 2003). An added benefit of including physical activity in a weight reduction program is the maintenance of bone health. Regular participation in physical activity also helps relieve boredom and stress, and promotes a positive self-image. Physical activity is also an effective strategy in preventing unhealthy weight gain in normal, overweight, and obese individuals. An expert panel assembled by the International Association for the Study of Obesity concluded that 45 to 60 minutes of daily exercise can help prevent normal-weight individuals from becoming overweight, overweight people from becoming obese, and already obese individuals from worsening their condition.

The latest physical activity guideline for adult is 60 minutes of physical activity per day to maintain body weight and prevent weight gain, and 60 to 90 minutes per day for the maintenance of weight loss. Duration and regular performance, rather than intensity, are the keys to success. One should search for activities that can be continued over time. In this regard, walking vigorously three miles per day can be as helpful as aerobic dancing or jogging if it is maintained. Moreover, activities of lighter intensity are less likely to lead to injuries. Some resistance exercise or weight training should also be added to increase lean body mass and, in turn, fat use. As lean muscle mass increases, so does one's basal metabolic rate. Various exercise strategies to maximize energy expenditure are discussed in detail in later sections of this chapter.

Modifying behavior

Behavior and attitude play an important role in supporting efforts to achieve and maintain appropriate body weight. In order to keep weight at a new lower level, food intake and exercise patterns must be changed for life. However, changing the hundreds of

Table 15.6 Selected food substitutes for reducing fat and caloric intake

Food class	*Higher fat foods*	*Low-fat alternative*
Dairy products	Whole milk	Fat-free (skim), low-fat (1%), or reduced-fat (2%) milk
	Whipping cream	Whipped cream made with fat-free milk
	Cream cheese	Light or fat-free cream cheese
	Cheese (cheddar, Swiss, American)	Low-calorie, reduced fat, or fat-free cheese
Cereals, grains, and pastas	Ramen noodles	Rice or spaghetti noodles
	Pasta with white sauce (alfredo)	Pasta with red/marinara sauce
	Pasta with cheese	Pasta with vegetables
	Granola	Bran flakes, oatmeal, or reduced granola
Meat, fish, and poultry	Regular hot dogs	Low-fat hot dogs
	Bacon or sausages	Canadian bacon or lean ham
	Regular ground beef	Ground turkey or extra lean ground beef
	Chicken or turkey with skin	Chicken or turkey without skin
	Oil-packed tuna	Water-packed tuna
	Beef (chuck, rib, brisket)	Beef (round, loin) trimmed of external fat
	Pork (spare ribs, untrimmed loin)	Pork tenderloin or trimmed, or lean smoked ham
	Frozen breaded or fried fish	Fresh or unbreaded fish
	Whole eggs	Egg whites or egg substitutes
Baked goods	Croissants, brioches, etc.	French rolls or soft brown rolls
	Donuts, sweet rolls, muffins, or pastries	English muffins, muffins with reduced fat, or bagels
	Party crackers	Low-fat crackers or saltine or soda crackers
	Cake (pound, chocolate, yellow)	Cake (angle food, white, gingerbread)
	Cookies	Reduced-fat or fat-free cookies (graham crackers, ginger snaps, fig bars)
Snack and sweets	Nuts	Popcorn, fruits, vegetables
	Ice cream	Sorbet, sherbet, low-fat or fat-free yogurt, or ice cream
	Custards or puddings made with whole milk	Puddings made with skim milk
Fats, oils, and salad dressings	Butter or margarine	Light spread or diet margarine, jelly, jam, or honey
	Mayonnaise	Light mayonnaise or mustard
	Salad dressings	Reduced-calorie or fat-free dressings, lemon juice, or plain, herb flavored, or wine vinegar
	Oils, shortenings, or lard	Using non-stick cooking spray for stir-frying or apple sauce, or prune puree for baked goods

small behaviors of overeating and under-exercising that lead to obesity requires time and effort. A person must commit to take action.

Changing behaviors requires identifying the old patterns that led to weight gain and replacing them with new ones to maintain weight loss. This may be accomplished through a process called behavior modification, which is based on the theory that behaviors involve (1) antecedents or cues that lead to the behavior, (2) the behavior itself, and (3) consequences of the behavior. For example, sitting in front of the television and mindlessly consuming a large bag of potato chips may leave you feeling bad because you consumed the extra calories. In this case the antecedent is watching TV, and behavior is mindlessly eating the chips, and the consequence is feeling remorse and gaining weight. The key to modifying this behavior is to recognize the antecedent, change the behavior, and replace the negative consequence with a positive one.

Therefore, to solve a problem one must first identify all the behaviors that created the problem in the first place. Keeping a record will help identify eating and exercise behaviors that may need changing. It will also establish a baseline against which to measure future progress. With so many possible behavior changes, a person can choose where to begin. Start simple and don't try to master them all at once. Attempting too many changes at one time can be overwhelming. Pick one trouble area that is manageable and start there. Practice desired behavior until it becomes routine. Then select another trouble area to work on, and so on.

Options for reducing energy intake

An ideal weight management program should provide for a reduction in energy intake along with education about meeting nutrient needs, increasing energy expenditure, and changing lifestyle patterns that led to the weight gain. Fad diets, such as those that emphasize eating primarily a single food, special foods, or specific combination of foods, may promote weight loss over the short term, but since they are not nutritionally sound they cannot be consumed safely for long periods. These fads do not encourage exercise or promote the changes in eating habits that affect body weight over the long term. If the program's approach is not the one that can be followed for a lifetime, it is unlikely to promote successful weight management. The following sections discuss some of the more common methods for reducing energy intake.

Low-calorie diets

Weight loss plans based simply on reducing energy intake are the most common choices. Some of the common plans include (1) fixed meal plans, (2) free-choice diets, (3) liquid formula diets, and (4) very low-calorie diets. Some recommend energy reduction without restricting types of foods selected, some use an exchange system to plan energy and nutrient intake, and others provide low-calorie packed meals and formulas.

Fixed-meal plans: These are diet plans in which you either choose from a limited list of food options or in which the entire menu is decided for you. For example, a fixed-meal plan may specify a cup of cornflakes with a banana for breakfast, tuna salad and an apple for lunch, and grilled chicken with broccoli for dinner. These diets are easy to follow and may make losing weight easier, but can be boring and thus are not practical for the long term. In addition, they don't teach food selection skills because the meals are predetermined.

Free-choice diets: These diets allow individuals to choose the foods they eat so long as the total caloric intake is reduced. They offer flexibility and variety, and can suit different preferences. This type of diet often uses a food-guide pyramid to construct a

balanced low-calorie diet. For example, a diet with as few as 1200 kcal can be planned by using the low end of a range of suggested servings and making low-calorie choices. These diets may not meet nutrient needs unless dieters are familiar with basic nutritional principles and diets are based on sound food selection guidelines.

Liquid formula diets: Liquid formula diets recommend a combination of food and formula to provide a daily energy intake of about 800 to 1200 kcal. They normally consist of two liquid meal replacements and a normal meal. The dieter can also snack on fresh fruit or vegetables. Liquid diets can lead to weight loss quickly, but this effect is purely short term. They can be very difficult to maintain due to the few calories that are permitted to be consumed. Liquid diets do not teach you how to eat in order to stay slim for the long term. They need to be accompanied by a behavior-changing course that deals with and prevents the reasons for overeating. Otherwise, it is easy to regain any weight lost on a liquid diet.

Very low-calorie diets: These diets are defined as those containing fewer than 800 kcal per day. They became popular in response to a desire for rapid weight loss. These diets provide little energy and a high proportion of protein. The protein in the diet will be used to meet the body's protein needs and will therefore prevent excessive loss of the body's protein. Often, very low-calorie diets are offered as a liquid formula. These formulae provide from 300 to 800 kcal and from 50 to 100 g of protein per day. They also contain the recommended daily requirements for vitamins, minerals, trace elements, and fatty acids. The initial weight loss is relatively rapid, about three to five pounds per week. However, in most cases, about 75 percent of this initial weight loss comes from water loss. Once initial weight loss ends, weight loss slows in part because the dieter's resting metabolism decreases to conserve energy, and physical activity decreases because the dieter often does not have the energy to continue their typical level of physical activity. Very low-calorie diets are no more effective than other methods in the long term and carry more risks. At these low-energy intakes, body protein is broken down and potassium is excreted. Depletion of potassium can result in irregular heartbeats, which can be fatal. Studies have also shown that in about one in four individuals following a very low-calorie diet for a few months, gallstones develop. Gallstone formation is facilitated by the more concentrated bile fluid and reduced flow as a result of the diet. Other side-effects include fatigue, nausea, light-headedness, constipation, anemia, hair loss, dry skin, and menstrual irregularities. It is recommended that very low-calorie diets be carried out in conjunction with medical supervision.

Diets that modify macronutrient intake

Rather than focusing on counting calories as a way of reducing body weight, some diets concentrate on modifying the proportion of energy containing nutrients. Currently, one of the biggest controversies is the role of dietary carbohydrate versus dietary fat in promoting weight loss. Weight loss diets that are low in fat and high in carbohydrates have long been considered the most effective in terms of weight management. In fact, as discussed in Chapter 10, the *Dietary Guidelines for Americans* advocate low-fat food choices with an emphasis on wholegrains, fruits, and vegetables. They suggest that we consume 45 to 65 percent of energy from carbohydrate, 10 to 35 percent from protein, and 20 to 30 percent from fat. However, Dr. Robert Atkins, one of the first pioneers of the low-carbohydrate diet, shocked the nutritional world in 1972 when he proposed that too much carbohydrate, rather than too much fat, may actually cause people to gain weight. Since then, there have been numerous diets developed that consist of an altered macronutrient distribution favoring a low-carbohydrate intake. Caution should be exercised in using these diets as they promote quick weight loss, limit food selections, and generally lack supporting evidence on safety and long-term efficacy.

Low-fat, high-carbohydrate diets: These diets contain approximately 10 percent of calories as fat and are very high in carbohydrates. The most notable are the "Pritikin Diet" and Dr. Dean Ornish's "Eat More, Weigh Less" diet plans. The diets advise dieters to avoid meat, dairy, oils, and olives; low-fat meat and dairy may be eaten in moderation. With an emphasis on fruits, vegetables, and wholegrains, the diets provide about 65 to 75 percent of total calories from carbohydrates, with proteins making up the difference.

There are several reasons why advocates of low-fat diets believe such diets help promote weight loss. Gram for gram, fat has twice as many calories as carbohydrate and protein. Therefore, it is reasonable to assume that consuming less fat may lead to low energy intake which in turn results in weight loss. Fat can also make foods more palatable, contributing to overconsumption. In addition, excess calories from fat are more readily stored by the body compared to those from carbohydrate and protein. This is due to energy cost associated with excess glucose and amino acids converted into fatty acids prior to storage. Recent studies suggest that low-fat diets benefit overall health by lowering total and LDL cholesterol concentrations, increasing HDL cholesterol concentrations, and improving blood glucose regulation (Lovejoy *et al.* 2003).

It must be kept in mind that low-fat diets are not always low in energy; even a diet low in fat will result in weight gain if energy intake exceeds energy output. This can be illustrated by the fact that the percentage of calories as fat in the typical American diet has decreased while the number of people who are overweight continues to increase. Although this dietary approach is not harmful, it is difficult to follow. People become quickly bored with this type of diet because they cannot eat many of their favorite foods. The diets emphasize a consumption of grains, fruits, and vegetables, which most people cannot sustain for very long.

Low-carbohydrate, high-fat, or high-protein diets: These diets are at the opposite end of the weight loss diet spectrum. Some of these diets, such as the introduction phase of the Atkins diet, severely restrict carbohydrate intake by prohibiting nearly all carbohydrate foods and allowing an unlimited quantity of meat and high-fat (~ 80–90% of the total energy intake) foods that are low in carbohydrate. Others, such as the Zone and South Beach diets, take a more moderate approach by allowing more proteins as well as fruits, vegetables, and wholegrains. One diet which has more recently become popular is the Ketogenic diet, which was initially used to treat epilepsy. The Ketogenic and Atkins diets are similar in terms of macronutrient composition, i.e., 5 percent carbohydrate, 60 percent fat, and 35 percent protein. However, with the Atkins diet, the dieter is able to introduce more carbohydrates (albeit still a very limited quantity) on completion of the initial introduction phase. Under the condition where bodily carbohydrate is limited, fatty acids can only be partially oxidized. As a result, more ketones will be produced. Ketones can be used as a source of energy. They can also suppress appetite, thereby making weight loss easier (refer to Figure 2.4). Low-carbohydrate diets have become popular in recent years, with almost 15 percent of Americans reporting that they are on some type of low-carbohydrate diet to lose weight. These diets are all based on the premise that a high-carbohydrate intake causes an increase in insulin levels, which promote storage of body fat.

Weight loss produced by this dietary approach appears to be short term and is largely attributed to water loss. As there will be 3 grams of water stored per gram of glycogen formed, the low-carbohydrate intake leads to less glycogen synthesis and less water in the body. A very low-carbohydrate intake also forces the liver to produce needed glucose. The source of carbons for this glucose is mostly protein from tissues such as muscle. Therefore, such production of glucose will result in a loss of lean body mass. Essential ions such as potassium are also lost in the urine. With the loss of glycogen stores, lean tissue, and water, dieters lose weight very rapidly. However, when a normal diet is resumed, weight is regained.

Studies comparing weight loss associated with low-carbohydrate diets and with low-fat diets showed that at six months a greater weight loss was achieved on low-carbohydrate diets. However, differences had disappeared by 12 months (Klein 2004). There is no compelling evidence to suggest that low-carbohydrate diets are more effective than other types of diets in helping people lose weight in the long run. Weight loss associated with low-carbohydrate diets may not necessarily be caused by an altered macronutrient distribution, but rather by a reduction in caloric intake as a result of limited food choice and increased ketosis (Bravata *et al.* 2003). Perhaps one of the biggest concerns regarding low-carbohydrate diets is that these diets contain too much total fat, saturated fat, and cholesterol and may lack essential macronutrients, dietary fiber, and phytochemicals rich in antioxidants. This dietary approach still awaits more evidence concerning its long-term efficacy and health consequences.

Exercise strategies in maximizing energy expenditure

Energy expenditure via **physical activity** or **exercise** typically accounts for about 30 percent of total daily energy expenditure. Physical activity and exercise have been used interchangeably in the past, but more recently, exercise has been referred to as physical activity that is planned, structured, repetitive, and purposive in the sense that the improvement or maintenance of one or more components of physical fitness is the objective (Caspersen *et al.* 1985). Pursuing exercise and physical activity regularly has long been part of recommendations made by various healthy organizations and authorities. This is because exercise and physical activity will enable individuals to increase their energy expenditure or create an energy deficit, while gaining cardiorespiratory fitness. It has been recommended that exercise in conjunction with dietary modification is the most effective behavioral approach for weight loss (National Health, Lung, and Blood Institute 1998).

Enhancing energy expenditure through physical activity

An exercise program typically used in a weight management program consists of continuous, large muscle activities with moderate to high caloric cost such as walking, running, cycling, swimming, rowing, and stair stepping. This approach will increase daily energy expenditure and help tip the caloric equation so that energy output is greater than energy input. Most training studies that have demonstrated exercise-induced weight loss have adopted exercise programs that elicit weekly energy expenditure of 1500 to 2000 kcal. This suggests that energy expenditure at a minimum of 300 kcal should be achieved during each exercise session and exercise should be performed no less than five times a week. This amount of energy expenditure generally occurs with 30 minutes of moderate to vigorous running, swimming, and cycling, or 60 minutes of brisk walking.

Energy expenditure during exercise can be influenced by **intensity**, **duration**, and modes of exercise. Unlike most fitness programs in which intensity of exercise plays an important part in exercise prescription, any program aimed at weight loss should ultimately be guided by the measure of total energy expenditure and its relation to energy consumption. In order to burn the most calories, exercise duration is considered more important, and exercise intensity must be adapted for the amount of time one would like to exercise (American College of Sports Medicine 2014). It has been suggested that exercise intensity should be tailored to allow a minimum of 300 kcal to be expended during each exercise session. Recent studies which include dietary modification have suggested that overweight women who exercise for a longer

duration each week are able to lose more weight during an 18-month intervention (Jakicic *et al.* 1999). In this study, individuals reporting >200 minutes of exercise per week also reported >2000 kcal wk^{-1} of leisure-time physical activity as measured by a questionnaire.

The higher the exercise intensity, the more the energy expenditure during exercise per unit of time. Stated alternatively, it costs you more energy to move your body weight or a given resistance at a faster pace. However, it is often difficult to maintain vigorous exercise for a sufficient period of time. This occurs especially in overweight or obese individuals who have low exercise tolerance in general. Some of them may also have the risk factors that contradict vigorous exercise. Consequently, those who need to maximize their energy expenditure may have to depend more on the expansion of exercise duration in order to achieve this goal. The American College of Sports Medicine (ACSM) position suggests that in order to be effective in maximizing energy expenditure long term, exercise intensity should not exceed 70 percent of an individual's maximal heart rate, which corresponds to ~60 percent of VO_2max or heart rate reserve (HRR) (Donnelly *et al.* 2009). This intensity allows the attainment of recommended exercise duration of ~45 minutes. The concept of mild exercise is also considered ideal for those who begin an exercise program. This will allow adequate time for individuals to adapt to their exercise routine and to progressively increase exercise intensity over time. It should be made clear that exercise at moderate to high intensities is proven effective in augmenting aerobic fitness. However, the level of exercise intensity necessary to improve fitness is generally higher than the level of exercise intensity necessary to facilitate energy expenditure and weight loss.

Exercise **frequency** complements duration and intensity. Frequency of exercise refers to how often each week one should perform exercise and is often determined based on how vigorous each exercise session is. It has been recommended that a training program consisting of exercise of moderate intensity (i.e., 50 to 70 percent VO_2max) be carried out no less than three times a week in order to develop and maintain cardiorespiratory fitness and improve body composition (American College of Sports Medicine 2014). More recent studies also suggest that energy expenditure necessary to bring about weight loss should be no less than 1500 kcal·$week^{-1}$. In order to achieve this threshold, energy expended during each exercise session should reach at least 500 kcal if exercise is performed three times a week, or 300 kcal if exercise is performed five times a week. Obviously, this latter exercise arrangement (i.e., >5 times $week^{-1}$) is more tolerated by sedentary and overweight individuals who often have difficulty sustaining vigorous exercise. The more frequent exercise regimen will also help in maximizing fat utilization and minimizing exercise-related injury (Wallace 1997).

As discussed earlier, in order to produce meaningful weight loss, one should attempt to achieve energy expenditure of at least 300 kcal during each exercise session. This amount of exercise expenditure corresponds to ~30 minutes of moderate-intensity exercise. If such activity can be performed three to four times a week, it will help in achieving a total of ~1000 kcal of energy expenditure each week. The caloric expenditure of ~1000 kcal·$week^{-1}$ is considered adequate for an overweight individual to begin an exercise intervention (Donnelly *et al.* 2009). This amount, however, has been found to be insufficient for long-term weight maintenance and should be increased progressively. Jakicic *et al.* (2001) observed that those who reported >2000 kcal·$week^{-1}$ physical activity showed no weight regain from 6 to 18 months of treatment, whereas there was significant weight regain observed in individuals who had energy expenditure below this threshold. Table 15.7 provides a summary of exercise guidelines as well as a sample prescription plan for maximizing energy expenditure and long-term weight control.

Table 15.7 Exercise guidelines and sample prescription plan for maximizing energy expenditure and long-term weight control

Component	*Guidelines*	*Sample prescription*
Mode	Exercises include low-impact and non-weight-bearing activities involving large muscle groups. Other non-conventional modes such as yoga, weight-lifting, or household activities may also be considered.	Walking, cycling, swimming, low-impact group exercise such as water aerobics.
Frequency	Exercise should be performed daily or at least five times per week. If necessary, a single session may be split into two or more mini-sessions.	Daily or 5–7 times a week.
Duration	Exercise duration should be maximized within the limit of tolerance and may be determined by time or caloric expenditure.	40–60 minutes a day, 20–30 minutes twice per day, or 150–400 kcal per day.
Intensity	Intensity should generally stay at the lower end of the target range and be determined in accordance with amount of time or calories one would like to accomplish.	40–70% VO_2max, 40–70% HRreserve, or 60–80% age-predicted HRmax.
Progression	In order to achieve successful weight loss and maintenance, there should be a progressive increase in the volume of exercise as intervention continues.	Proper increment in exercise volume should be made gradually as one's tolerance increases. Both intensity and duration may eventually reach the upper end of their respective range.

Exercise intensity and fat utilization

Will mild exercise be superior in facilitating fat utilization? As discussed in Chapter 9, exercise at lower intensities is associated with a lower respiratory exchange ratio which suggests a greater percentage of energy derived from fat oxidation. This observation has resulted in a current myth that in order to burn fat you must exercise at a lower percentage of your maximal oxygen uptake (VO_2max). It may also explain the growing popularity of "fat-burner" classes, which assume that low-intensity exercise will lead to increased weight loss. It must be made clear that at higher intensities, though the percentage of the total calories derived from fat is lower, the total energy expenditure resulting from exercise can be higher, especially if accompanied by sufficient exercise duration. Consequently, the absolute quantity of calories burned due to fat oxidation may also be higher. We made a comparison of fat metabolism during exercise between 50 and 70 percent VO_2max using data collected from our laboratory. As shown in Table 15.8, those who exercise at 50 percent VO_2max consume oxygen at 1 liter per minute and respiratory exchange ratio is 0.86. At this ratio, according to Table 13.3, a total of 4.875 calories per min ($1\,l\,min^{-1} \times 4.875\,kcal\,l^{-1}$) are expended and 2.24 or 46 percent of these are fat calories. On the other hand, for those who exercise at 70 percent VO_2max, their oxygen consumption and respiratory exchange ratio are 1.5 liter·min^{-1} and 0.88, respectively. As a result, a total of 7.349 calories per minute ($1.51\,l\,min^{-1} \times 4.899\,kcal\,l^{-1}$) are expended and 2.87 or 39 percent of these are fat calories. Although this is a lower percentage of fat calories, it is a higher total number of fat calories. From this example, it is clear that even though a greater percentage of fat is elicited at a lower level of exercise intensity, this does not necessarily mean that more quantity of fat is burned.

One may always try to pursue an exercise routine of sufficient intensity that will bring about a decent level of total energy expenditure. However, exercise intensity should be carefully chosen to prevent premature fatigue and to allow an exercise program to continue. Exercise duration could decrease drastically if intensity is set too high or exceeds the **lactate threshold**, the intensity at which blood lactic acid begins to accumulate drastically. Based on the current literature, exercise at 60 to 65 percent VO_2max would help in eliciting a maximal rate of fat oxidation (Achten *et al.* 2002). The intensity at which fat oxidation peaks is denoted as $\mathbf{Fat_{max}}$, and this intensity coincides closely with lactate threshold. For most individuals, exercising at Fat_{max} can allow them to achieve the recommended energy expenditure within 30 to 45 minutes. As such, this intensity appears to be effective in maximizing both fat utilization and total energy expenditure in a time-efficient manner.

Performing more vigorous exercise has also been related to a greater reduction in fat from the abdominal area. This was evidenced by a number of epidemiological studies that involved middle-aged and elderly individuals (Buemann and Tremblay 1996,

Table 15.8 Comparisons of fat and total calories expended during stationary cycling at 50 and 70 percent VO_2max

Metabolic variables	*Exercise intensity*	
	50% VO_2max	*70% VO_2max*
Oxygen uptake (l·min^{-1})	1.0	1.5
Respirator exchange ratio	0.86	0.88
Caloric equivalent (kcal^{-1}l)	4.875	4.899
Energy output (kcal·min^{-1})	4.875	7.349
Relative fat contribution (%)	46	39
Fat calories (kcal·min^{-1})	2.24	2.87

Tremblay *et al.* 1990 and 1994, Visser *et al.* 1997). For example, Visser *et al.* (1997) found that intensive exercise such as playing sports was negatively associated with abdominal fat. Tremblay *et al.* (1990) also observed a preferential reduction in abdominal fat in those who performed more intensive exercise. This association that favors the use of more vigorous exercises may be explained by the fact that the fat stored in the abdominal area can be more easily degraded during high-intensity exercise compared to the fat stored in other tissues. It has been found that lipolysis is subject to the influence of epinephrine, which increases with increased exercise intensity (Wahrenberg *et al.* 1991).

Other exercise strategies

Exercise intensity and duration are the two prescription indices that are often used to develop an effective yet safe exercise program. An easy application of such prescription is to have a steady-state exercise being performed at target intensity for a desired duration. In reality, however, many exercise sessions are conducted in a more complex fashion. For example, a single exercise session may be divided into two or three smaller sessions performed at different times of the day so that the target caloric expenditure can be achieved via accumulation. In many cases, despite the provision of target intensity, an exercise is performed with intensity being fluctuated such as interval training that involves alternating short periods of intense exercise with less intense recovery periods. In addition, recent evidence suggests that resistance training be included in a comprehensive weight loss program to maximize its effectiveness.

Intermittent exercise

A few studies have examined the efficacy of adopting **intermittent exercise** for weight management (Donnelly *et al.* 2000, Jakicic *et al.* 1995, 1999). This direction of research was driven by a question as to whether the same metabolic and weight loss benefits can be achieved by exercising in multiple sessions of shorter duration throughout the day. Intermittent exercise is typically defined as the accumulation of 30 to 40 minutes of exercise each day through participation in multiple 10- to 15-minute exercise sessions daily. This exercise strategy is considered advantageous for those who dislike or are unable to tolerate continuous exercise, or who have a daily schedule that prohibits a typical workout session to be carried out. Intermittent exercise has long been proven effective in improving exercise compliance and enhancing cardiorespiratory fitness and improving risk factors for cardiovascular diseases. Its direct impact upon energy metabolism and weight loss has also been recognized. Jakicic *et al.* (1995) reported that exercising in multiple short bouts per day was just as effective as a single long exercise session in producing weight loss while gaining cardiorespiratory fitness over a 20-week intervention period that included dietary modification. In this same study, the program of multiple short bouts of exercise was also found to increase exercise adherence, which implies that this exercise strategy has the potential to facilitate the long-term adoption of a weight loss program and thus to prevent weight regain.

Whether performing multiple short sessions of exercise instead of a long exercise bout will elicit more energy expenditure is another intriguing question that emerged recently. The total energy expenditure of a single exercise session includes the energy expended during the actual exercise period as well as that during the recovery period following exercise; the latter is referred to as excessive post-exercise oxygen consumption (EPOC). As mentioned earlier, EPOC may be viewed as a compensatory response resulting from a disruption to homeostasis caused by the preceding exercise. In this context, it may be speculated that exercise of shorter duration performed more than

once daily would be associated with a greater EPOC due to multiple occurrences of recovery. Almuzaini *et al.* (1998) have found that splitting a 30-minute session into two 15-minute sessions elicited a greater overall post-exercise VO_2. Although the long-term impact of this exercise arrangement upon energy metabolism and weight loss remains to be elucidated, exercising for 20 to 30 minutes twice daily has been adopted as an alternative approach for those with chronic conditions, including cardiovascular, neuromuscular, and metabolic disorders (Wallace 1997).

Variable intensity protocols

In line with the concept of EPOC, we recently examined whether an aerobic exercise performed at variable intensities, such as Spinning®, would produce greater energy expenditure (Kang *et al.* 2005a). This type of exercise has gained popularity within recent years because it replicates the experience of outdoor cycling during which intensity often varies and is considered more effective in engaging exercise participants, especially when conducted to the accompaniment of music and/or visualization (Francis *et al.* 1999). In this study, we found a greater EPOC following the variable intensity or Spinning® exercise as compared to the constant intensity exercise even though the average intensity was kept the same. We attributed this greater EPOC to the fact that intensity fluctuated during variable intensity exercise, which may have disturbed homeostasis to a greater extent. This exercise arrangement was also found to be associated with a greater accumulation of blood lactic acid. However, the level of exertion during the entire workout was not perceived to be any harder than the constant intensity exercise, which makes this variable intensity protocol more attractive to those who seek to maximize energy expenditure while participating in an exercise program. It should be noted that a variable intensity exercise regimen differs from conventional interval training protocols in that the former is the exercise in which there is no rest period and intensity fluctuates in a repeating pattern and with a smaller magnitude.

High-intensity interval training

High-intensity interval training (HIIT) involves a repeated series of short bouts of high- (near maximum) intensity exercise interspersed with a brief rest or low-intensity activity. The total workout duration usually lasts for no more than 20 minutes. The most common model employed in this type of training consists of four to six bouts of 30-second all-out cycling effort against a supramaximal workload separated by ~4 minutes of recovery (Gibala *et al.* 2012). One may make this model less intense by lengthening workouts but reducing rest periods, i.e., 10×60-second work bouts at an intensity that elicits ~90 percent of maximal heart rate, interspersed with 60 seconds of recovery. HIIT may easily be modified for people of all fitness levels and special conditions, such as overweight and diabetes. HIIT may be performed on all exercise modes, including cycling, walking, swimming, aqua training, elliptical cross-training, and in many group exercise classes. HIIT workouts typically last for a shorter time, but provide comparable fitness benefits compared to continuous endurance workouts. This is mainly because HIIT workouts are associated with greater post-exercise energy expenditure compared to traditional steady-state exercise (see Figure 15.3). Because of the vigorous nature of HIIT, the EPOC associated with HIIT can add up to 15 to 20 percent more calories to the overall workout energy expenditure, it is usually no more than 10 percent for an aerobic session. A growing body of evidence demonstrates that when compared to traditional endurance-based training on a matched-work basis, HIIT can induce similar or even superior physiological adaptations including increases in glucose tolerance,

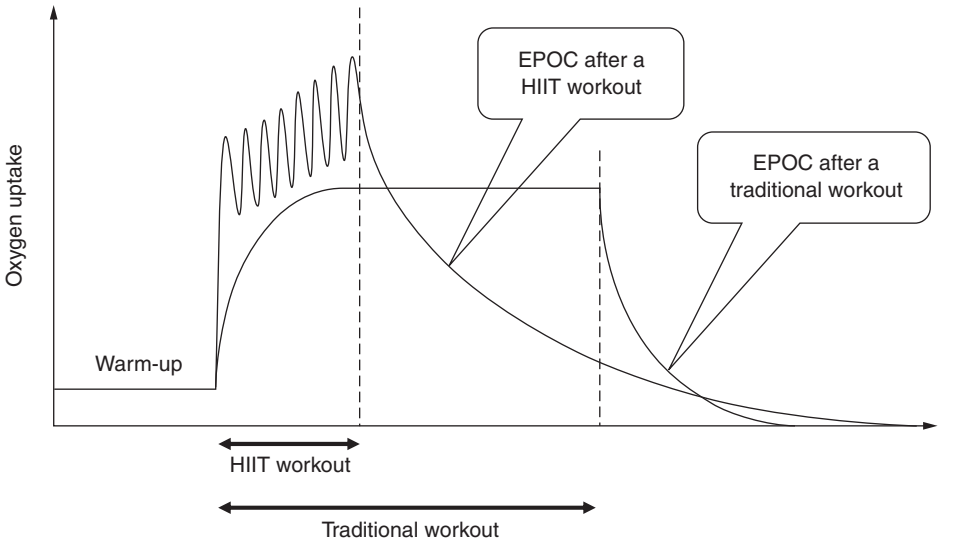


Figure 15.3 Comparisons of metabolic rate during and after HIIT vs. traditional workout

insulin sensitivity, and skeletal muscle oxidative capacity (Burgomaster *et al.* 2008, Gibala *et al.* 2012). Such findings are important given that "lack of time" remains the most commonly cited barrier to regular exercise participation.

A question remains as to whether the general population could safely tolerate the extreme nature of this exercise regimen. Persons who have been living relatively sedentary lifestyles or periods of physical inactivity may have an increased coronary disease risk to high-intensity exercise. It is recommended that medical clearance from a physician be obtained as a safety measure for anyone who wants to start HIIT. Prior to beginning HIIT training, a person is encouraged to establish a base fitness level, which is consistent aerobic training three to five times a week for 20 to 60 minutes per session at a relatively high intensity for several weeks that produce certain cardiorespiratory and muscular adaptations. Establishing appropriate exercise form and muscle strength is important before engaging in regular HIIT.

Resistance exercise

Resistance training is a potent stimulus to increase fat-free mass (FFM), which may help in preserving lean body mass while reducing body weight and body fat. An increase in FFM will also help maintain or augment the resting energy rate, which accounts for about 60 percent of total daily energy expenditure (Poehlman and Melby 1998). The resting metabolic rate is primarily related to the amount of FFM. It is known that the resting metabolic rate decreases with advancing age at a rate of 2 to 3 percent per decade and this decrease is primarily attributed to the loss of FFM. So, incorporating resistance training is especially important as people age and can help counteract the age-related decrease in neuromuscular function and resting energy expenditure.

Resistance training also improves muscular strength and power. This adaptation is necessary in terms of athletics. It also allows an ordinary individual to be more capable

of performing daily tasks such as carrying, lifting, and changing body posture. The improvement in muscular strength may not impact energy balance directly. However, it will facilitate the adoption of a more active lifestyle in sedentary overweight and obese individuals (Donnelly *et al.* 2009). Some other metabolic benefits of resistance training may include improvement in blood lipid profile and increase in fat oxidation (Kokkinos and Hurley 1990, Van Etten *et al.* 1995, Treuth *et al.* 1995).

As with other forms of exercise, resistance training increases energy expenditure during both exercise and recovery. However, resistance exercise differs from aerobic exercise in that its energetic contribution to daily total energy expenditure is very small. Energy expenditure during a typical weight-lifting workout ranges from 100 to 200 kcal, a figure that is less than a half as much as what is normally achieved during a single session of aerobic exercise. On the other hand, resistance training can trigger a profound increase in post-exercise oxygen consumption due to the fact that the exercise is performed intermittently at a very high intensity. In fact, a number of studies have found that the average oxygen consumption following resistance exercise is even greater than that following aerobic exercise when both types of exercise were equated for total energy expenditure (Gillette *et al.* 1994, Burleson *et al.* 1998).

Similar to cardiorespiratory fitness, the resistance training prescription should be made based on the health and fitness status and the specific goals of the individual. For weight management purposes, the major goal of the resistance training program is to develop sufficient muscular strength so that an individual is able to sustain a regular training routine and at the same time to live a physically independent lifestyle. In order to maximize energy expenditure, a circuit weight-training program may be introduced in order to allow individuals to work on multiple muscle groups (i.e., gluteals, quadriceps, hamstrings, pectorals, latissimus dorsi, deltoids, and abdominals) in one session that may last for as long as 60 minutes. The metabolic advantage is that this training format involves multiple sets of low-intensity (i.e., 40 percent 1-RM) and high repetitions (i.e., 10 to 15 repetitions) on each muscle group, coupled with a relatively shorter rest interval between sets (i.e., ~15 seconds). In addition to more energy expended during the workout, this type of training also elicits greater EPOC as compared to regular strength-training programs. It is recommended that resistance training be performed at least twice a week, with at least 48 hours of rest between sessions to allow proper recuperation (American College of Sports Medicine 2014).

Limitations of exercise alone in weight management

Despite the ability of physical activity and exercise to create a negative caloric balance, the actual impact of exercise alone upon weight loss is often found to be minimal (Garrow 1995, Wilmore 1995, Saris 1993). Although there is a negative association between the level of physical activity and the prevalence of obesity and those who are physically active tend to be leaner, it remains unclear as to the extent to what physical activity or exercise can do, even combined with dietary restriction, in treating those who are already overweight and obese. In a meta-analysis of 493 studies over a 25-year period, Miller *et al.* (1997) reported that exercise alone has a relatively minor effect on weight loss and does not add much to the weight loss effect of a reduced diet. There are some studies that have demonstrated the positive effect of exercise on weight loss (Ross *et al.* 2000). However, the exercise intervention adopted was relatively vigorous and resulted in an energy deficit of 700 kcal per day, a caloric value twice as much as that which is normally recommended to achieve during an exercise session. It appears that in order for physical activity and exercise to have a major impact upon body weight reduction, the exercise prescription should entail exercising daily, with each exercise being

performed at moderate to high intensity for more than an hour. Obviously, most obese individuals cannot tolerate and sustain this exercise dosage.

The weak effect of exercise alone on weight loss may be explained by the fact that when people begin exercise training, they tend to rest more after each exercise session, which negates the calories expended during exercise. One should also realize that the amount of energy expended during exercise that is suitable to sedentary or obese individuals is actually relatively small. For example, the net energy cost during a three-mile brisk walk for a 70-kilogram or 154-pound obese woman is only about 150 to 160 kcal (215 total calories minus 50 calories for the BMR). Given that 1 pound of fat contains 3500 calories, it would take nearly a month of daily walking of three miles to lose 1 pound of fat if all else stays the same. Exercise by itself being ineffective in weight loss may not be attributed to the claim that people will eat more when they become more active. In fact, in those studies that failed to demonstrate the effect of added exercise, the exercise intervention was implemented under controlled dietary conditions in which all subjects whether treated with exercise or not were fed a similar diet.

From a public health standpoint, despite such potential limitations of exercise alone in weight management, it seems prudent to conclude that any exercise is better than none and, within the range of tolerance, more is probably better. Still, regular physical activity has proven beneficial in many aspects irrespective of body weight control such as improving cardiorespiratory fitness, augmenting an overall feeling of well-being, and reducing risk factors for developing chronic conditions such as coronary heart disease, hypertension, diabetes, and osteoporosis.

Summary

- According to the set-point theory, there is a control system built into every person dictating how much fat he or she should carry – a kind of thermostat for body fat. The set point for body fatness is determined by genetics. Some individuals have a high setting, others have a low one. In an obese individual, body fat is set to remain at a higher level than it is in a lean individual.
- Body fatness is regulated through the interaction of the brain with an array of afferent signals from various body systems. Signals from the gastrointestinal tract, hormones, and circulating nutrients regulate short-term hunger and satiety. Signals such as the release of leptin from fat cells regulate long-term energy intake and expenditure.
- Leptin functions to help with body weight regulation by decreasing energy intake and increasing energy expenditure. Defects in the leptin signaling system cause the brain to assess adipose tissues status improperly and thus impair body weight regulation. Many obese people are found to have high levels of leptin, suggesting that these individuals may have developed resistance to respond to these hormones.
- The total energy expenditure on any given day may be further divided into (1) resting energy expenditure (RMR), (2) thermal effect of food, and (3) energy expenditure during physical activities. Quantitatively, RMR accounts for about 60 to 75 percent of the total daily energy expenditure. It is due to this large fraction that RMR has attracted a great deal of attention with regard to its role in mediating weight gain and obesity.
- Upon completion of an exercise, VO_2 does not return to resting levels immediately, but does so relatively gradually. This elevated oxygen consumption following exercise has been referred to as excess post-exercise oxygen consumption (EPOC). EPOC represents energy necessary to restore homeostasis that is disrupted during the proceeding exercise and its quantity is proportional to the level of exercise intensity.

- In contrast to aerobic exercise, resistance exercise is often performed in an intermittent fashion. Exertion can be very strenuous, but is usually sustained for no more than a minute. The energy cost of an entire session of resistance training is usually lower than most aerobic exercises. However, such training can produce significant EPOC. Circuit weight-training is by far the best choice for promoting energy expenditure through resistance exercise.
- The thermic effect of feeding may be divided into two subcomponents: obligatory and facultative thermogenesis. The obligatory component is the energy used for digestion, absorption, assimilation, and storage, whereas the facultative component is an additional increase in energy expenditure caused by the meal-induced activation of the sympathetic nervous system.
- Of three macronutrients, consumption of protein is most thermogenic and its energy cost can reach 20 to 30 percent of total energy intake. This is followed by carbohydrate (5 to 10 percent) and then fat (0 to 5 percent). The greatest thermic effect associated with protein may be mainly ascribed to the extra energy needed for its digestion and absorption by the gastrointestinal tract as well as deamination of amino acids and synthesis of protein in the liver.
- Heredity may predispose one to obesity. However, environmental factors are also highly involved. When genetically susceptible individuals find themselves in an environment where food is appealing and plentiful and physical activity is easily avoided, obesity is a likely outcome. Among those environmental factors are (1) high-calorie and fat intake; (2) reduced energy expenditure due to technology advancement, and (3) personal choices concerning the amount and type of food consumed.
- Treatment of overweight and obesity should be long term, similar to that for any chronic disease. It requires a firm commitment to lifestyle changes, rather than a quick fix as promoted by many popular diet books. An ideal weight management program should provide for a reduction in energy intake along with education about meeting nutrient needs, increasing energy expenditure, and changing lifestyle patterns that led to weight gain in the first place.
- Studies comparing weight loss associated with low-carbohydrate diets and with low-fat diets showed that at six months a greater weight loss is achieved on low-carbohydrate diets. However, differences disappeared by 12 months. There is no compelling evidence that low-carbohydrate, high-fat/protein diets are more effective than other types of diets in helping people lose weight in the long run.
- The specific weight management strategies include (1) increase physical activity more than energy consumed from food; (2) make nutritional adequacy a priority and emphasize foods with a low energy density and a high nutrient density; (3) limit high-fat foods: make legumes, wholegrains, vegetables, and fruits central to your diet plan; (4) eat small portions; (5) limit concentrated sweets and alcoholic beverages, and (6) keep a record of diet and exercise habits.
- Aerobic training is proven effective in weight control and management. It helps increase energy expenditure via repeated muscle contractions. It also augments fat utilization and this may be explained in part by an improved transport of oxygen and fatty acids due to increased capillary density of muscle tissue being trained.
- Exercise intensity and duration are the two important measures of exercise prescription. Unlike most fitness programs in which intensity of exercise plays an important part of the exercise prescription, any program aimed at weight loss should ultimately be guided by the measure of total energy expenditure and its relation to energy consumption. In order to burn the most calories, exercise duration is considered more important, and exercise intensity must be adapted to the amount of time or calories one would like to accomplish.

- Contrary to the common myth, it appears that a relatively more vigorous exercise program is necessary in order to facilitate fat utilization. Exercise intensity that elicits maximal rate of fat oxidation was found to be about 60 to 65 percent VO_2max. This finding may be explained in part by the fact that the process of lipolysis is intensity dependent.
- Exercise strategies for weight management should include not only constant-load exercises but also those performed in a more complex fashion such as intermittent, variable intensity, interval training, and resistance exercise protocols. In general, these protocols consist of a series of more intense but shorter exercise bouts interspersed with rest or less intense recovery periods, require less total exercise time, and are associated with greater energy expenditure post exercise.
- Circuit weight training allows individuals to work on 8 to 10 major muscle groups in one session that may last for as long as 60 minutes. It involves multiple sets of low intensity and high repetitions coupled with a relatively shorter rest interval between sets. It can stimulate both muscular and cardiorespiratory systems effectively. Hence, it may be the choice for those who are interested in losing fat tissue while gaining muscle mass.

Case study: balancing energy intake and energy output

Joe is unhappy about the 20 pounds he gained during his first two years at college. He is 21 years old, 5 feet 7 inches tall, and weighs 180 pounds. He would like to weigh around 160 pounds. In analyzing why he gained weight, Joe realizes that he has a hectic schedule. While studying full time, Joe also works 30 hours a week at a warehouse distribution center filing orders. During his leisure time, Joe likes to watch sports on TV, spend time with friends, and study. Joe has little time to think about what he eats. On a typical day, he stops for coffee and a pastry on his way to class in the morning, has a burger and pizza for lunch in a quick-service restaurant, and picks up fried chicken or fish at the drive-through on his way to work. He gets less exercise than he used to and often eats cookies or candy bars while studying late at night. By recording and analyzing his food intake for three days, Joe found out that he takes in about 3200 kcal per day. He also calculated his estimated energy requirement just to see how this compares to his recommended intake. By keeping an activity log, he estimated that his typical day includes 30 minutes of low to moderate activity, such as brisk walking, which puts his activity level in the "low active" category.

Questions

- What is Joe's estimated energy requirement (EER)? How does his EER compare to his caloric intake? (Hint: See EER equations in Chapter 8.)
- What changes could Joe make in his diet that would promote weight loss?
- What aspects of Joe's lifestyle (other than diet) are causing his weight gain? How should he change them in order to promote weight loss and maintenance?

Review questions

1 Define the terms (1) hunger, (2) satiety, (3) appetite, and (4) hypothalamus.
2 Discuss the role leptin plays in regulation body weight.
3 Define the term resting metabolic rate. What is resting metabolic rate for an average man and an average woman?

4 What are the factors that have been considered in calculating one's resting metabolic rate, i.e., Harris–Benedict equations?
5 What is the thermic effect of feeding? How does it differ between consumption of protein, carbohydrate, and fat?
6 What is the difference between obligatory thermogenesis and facultative thermogenesis?
7 Explain each of the following low-calorie diets: (1) fixed-meal plan, (2) free-choice diets, (3) liquid formula diets, and (4) very low-calorie diets.
8 Describe the differences in macronutrient distribution between a balanced and a low-carbohydrate diet.
9 How is weight loss brought about by (1) high-carbohydrate, low-fat diets, and (2) low-carbohydrate, high-fat diets? Which one is more effective?
10 What are ketones? Explain how ketones are produced in the body.
11 What role does physical activity play in weight management? List the potential benefits of physical activity that are independent of weight loss.
12 Define the terms intensity, duration, frequency, and progression. How would you use these terms in establishing an exercise program for people who want to loss excess body fat?
13 What is EPOC? How is this term applied in weight loss scenarios?
14 How is circuit weight training carried out? What are the advantages of using this type of resistance training program?
15 What may be the weight loss advantage of using short duration and high-intensity interval training? What could be the potential risks associated with this type of exercise?

Suggested reading

1 Baile CA, Della-Fera MA, Martin RJ (2000) Regulation of metabolism and body fat mass by leptin. *Annual Review of Nutrition*, 20: 105–127.
This paper discusses the role leptin plays in maintaining a stable body weight over the long term despite the fact that a variety of environmental conditions alter short-term energy intake.
2 Donnelly JE, Blair SN, Jakicic JM, Manore MM, Rankin JW, Smith BK, American College of Sports Medicine (2009) American College of Sports Medicine Position Stand. Appropriate physical activity intervention strategies for weight loss and prevention of weight regain for adults. *Medicine and Science in Sports and Exercise*, 41: 459–471.
Overweight and obesity affects more than two-thirds of the adult population and is associated with a variety of chronic diseases. This position stand provides evidence-based guidelines as to how an exercise prescription should be made in order to facilitate weight loss and prevent weight regain.
3 Hill JO (2006) Understanding and addressing the epidemic of obesity: an energy balance perspective. *Endocrine Review*, 27: 750–761.
This paper helps readers further understand the etiology of obesity. It focuses on how behavioral and environmental factors have interacted to produce a positive energy balance that results in weight gain.
4 Paddon-Jones D, Westman E, Mattes RD, Wolfe RR, Astrup A, Westerterp-Plantenga M (2008) Protein, weight management, and satiety. *American Journal of Clinical Nutrition*, 87: 1558S–1561S.
Diets high in protein are popular in treating overweight and obesity. This article provides additional evidence to support the potential benefits associated with a moderately elevated protein intake.

Glossary

Appetite the drive to eat specific foods that is not necessarily related to hunger.

Basal metabolic rate the energy expenditure measured immediately after awakening in the morning.

Circuit weight training a weight training routine consisting of 10 to 12 resistance exercises for both the upper and lower body executed in a planned fashion with limited rest between exercises.

Duration the length of time physical activity continues and can also be expressed in terms of the total number of calories expended.

Excess post-exercise oxygen consumption (EPOC) the amount of extra oxygen required by the body during recovery from prior exercise.

Exercise physical activity that is planned, structured, and repetitive, and purposive.

Facultative thermogenesis the diet-induced thermogenesis mediated by the activation of the sympathetic nervous system.

Fat_{max} an exercise intensity at which fat oxidation rate peaks.

Frequency rate of occurrence within a given period of time or a number of exercise sessions completed every week.

Ghrelin a hormone produced by the stomach in response to a lack of food and triggering hunger.

High-intensity interval training an exercise that involves a repeated series of short bouts of high (near maximum) intensity exercise interspersed with a brief rest or low-intensity activity.

Hypothalamus a portion of the brain that contains neural centers, helping regulate appetite and hunger.

Intensity the state of exertion or quality of being intense and can be expressed using heart rate, oxygen consumption, blood lactate concentration.

Intermittent exercise an exercise regimen during which exercise stops and resumes in an alternate fashion.

Lactate threshold the intensity at which blood lactic acid begins to accumulate drastically.

Negative energy balance a condition where energy input is smaller than energy output.

Obligatory thermogenesis the diet-induced thermogenesis due to digestion and absorption as well as the synthesis of protein, fat, and carbohydrate to be stored in the body.

Oxygen deficit a lag of oxygen consumption at the onset of exercise computed as the difference between oxygen uptake during the early stages of exercise and during a similar duration in a steady state of exercise.

Physical activity muscular contraction that increases energy expenditure.

Positive energy balance a condition where energy input is greater than energy output.

Resting metabolic rate (RMR) the energy expenditure typically measured three to four hours after a light meal without prior physical activity.

Set point a control system built into every person dictating how much fat he or she should carry.

Settling-point theory refers to the idea that the set point may be modified, and, in the case of weight gain, is re-established at a higher level.

Thermal effect of food (TEF) an increase in energy expenditure associated with consumption of foods.

Weight cycling repeated cycles of weight loss and regain that may increase the proportion of body fat with each successive weight regain and cause a decrease in RMR, making subsequent weight loss more difficult.

16 Thermoregulation and fluid balance

Contents

Key terms

- Aldosterone
- Anti-diuretic hormone
- Conduction
- Convection
- Dehydration
- Evaporation
- Gastric emptying
- Glucose electrolyte solutions
- Glucose polymer solutions
- Heat acclimatization
- Hyperhydration
- Hyponatremia
- Involuntary heat production
- Maltodextrin
- Non-shivering thermogenesis
- Osmolality
- Radiation
- Relative humidity
- Rhabdomyolysis
- Stroke volume
- Thirst
- Voluntary heat production

Thermoregulation at rest and during exercise

In humans, normal body temperature is approximately 37°C (98.6°F). This value refers to the internal or core temperature, which is commonly measured orally and rectally. On the other hand, shell temperature, which represents the temperature of the skin and the tissues directly beneath it, varies considerably depending on the surrounding environmental temperature. At rest, rectal temperature is normally 0.5 to 1°F higher than oral temperature; however, it was reported that following a road race rectal temperature was 5.5°F higher than oral temperature, suggesting that an oral reading may not be an accurate reflection of the true body temperature. The fact that the body is able to maintain its temperature is achieved by controlling the rate of heat production and the rate of heat loss. As shown in Figure 16.1, body temperature reflects a delicate balance between heat production and heat loss. When out of balance, the body either gains or loses heat. The temperature control center, which is located in the hypothalamus, works like a thermostat; it can initiate an increase in heat production when body temperature falls and an increase in heat loss when body temperature rises.

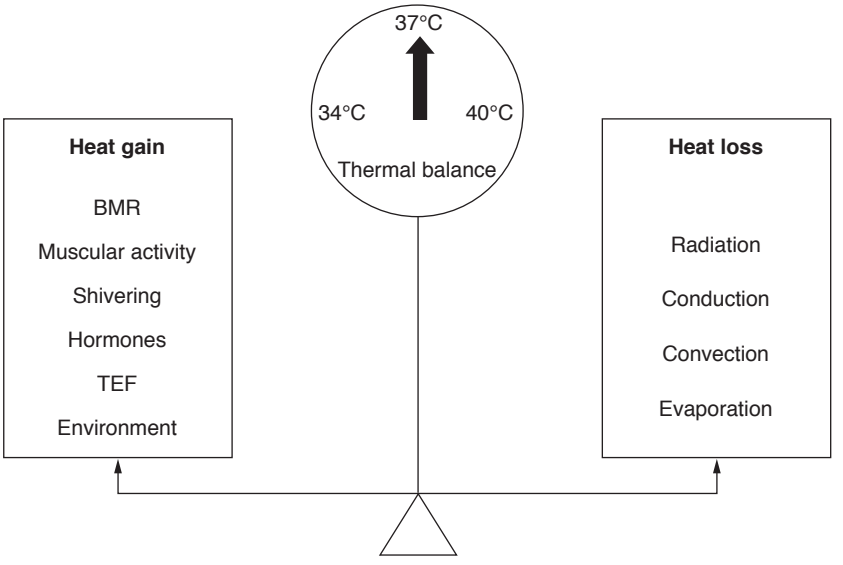


Figure 16.1 Factors that contribute to body temperature homeostasis

Heat production

The body produces internal heat due to normal metabolic processes. Metabolic heat production is low at rest or during sleep. However, during intense exercise heat production is high. Heat production may be classified as voluntary and involuntary. **Voluntary heat production** is brought about by exercise or physical activity, whereas involuntary heat production results from shivering or the secretion of hormones, such as thyroxine and catecholamines. Increased muscular activity during exercise causes an increase in heat production in the body owing to the inefficiency of the metabolic reactions that provide energy for contraction. The body is, at most, 20 to 30 percent efficient. Therefore, 70 to 80 percent of the energy expended during exercise appears as heat. The total amount of heat produced in the body depends on the intensity and duration of the exercise. A more intense exercise will produce heat at a faster rate, while the longer the exercise lasts, the more the total heat is produced.

During intense exercise this can result in a high heat load. As discussed in Chapter 13, each liter of oxygen used is equivalent to the production of 5 kcal. Therefore, for every liter of oxygen consumed during exercise, approximately 16 kJ (4 kcal) of heat is produced and only about 4 kJ (1 kcal) is actually used to perform mechanic work. Therefore, for an athlete consuming oxygen at a rate of 41 min^{-1} during exercise, the rate of heat production in the body is about 16 kcal min^{-1} or 960 kcal h^{-1}. It is estimated that at an intensity equivalent to about 80 to 90 percent VO_2max, the amount of heat produced in a fit individual could potentially increase body temperature by 1°C (1.8°F) every 4 to 5 minutes if no changes occur in the body's heat dissipation mechanism.

A normal body temperature at rest ranges from 36° to 38°C (97° to 100°F) and may rise to 38° to 40°C (100° to 104°F) during exercise. Further increases may result in heat exhaustion and subsequently heat-stroke (both of which will be discussed later in this chapter). The elevated body temperature during exercise is not caused by resetting the hypothalamic set point. Rather, it is caused by the temporary imbalance between the rates of heat production and heat dissipation during early stages of exercise. A more rapid response of heat dissipation mechanisms can attenuate or delay the exercise-induced rise in body temperature. This can then allow an athlete to compete at a relatively lower body temperature in a hot/warm environment. One of the heat acclimatization responses is that athletes will be able to respond to the heat more quickly on the commencement of exercise.

Involuntary heat production by shivering is the primary means of increasing heat production during exposure to cold. Maximal shivering can increase the body's heat production by approximately five times the resting values. In addition, the release of thyroxine from the thyroid gland can also increase heat production. Thyroxine acts by increasing the metabolic rate of all cells in the body. Finally, an increase in blood level of catecholamines (epinephrine and norepinephrine) can cause an increase in the rate of cellular metabolism. The increase in heat production due to the combined influences of thyroxine and catecholamines is also referred to as **non-shivering thermogenesis**.

Environmental factors, such as air temperature, relative humidity, and air movement, will also affect heat stress imposed upon an active individual. Caution should be advised when the air temperature is 27°C (80°F) or higher. However, if the relative humidity and solar radiation are high, lower air temperature – even 21°C (70°F) – may still pose a risk of heat stress during exercise. As the water content in the air increases, the relative humidity rises. The increased humidity impairs the ability of sweat to evaporate and may thus restrict the effectiveness of the body's main cooling system when exercising. With humidity levels close to 90 to 100 percent, heat loss via evaporation nears zero. Therefore, extra caution should be used when the relative humidity exceeds 50 to 60 percent,

especially when accompanied by warmer temperatures. Thermal balance may also be affected by air movement. Still air hinders heat carried away by convection. Even a small breeze may help keep body temperature near normal by moving heat away from the skin surface.

Heat dissipation

For the body to transfer heat to the environment, the heat produced in the body must have access to the outside world. The heat from deep in the body (the core) is moved by the blood to the skin (the shell). Once heat nears the skin, it can be transferred to the environment by any one of four mechanisms: conduction, convection, radiation, and evaporation. These mechanisms function to protect the body from overheating. Figure 16.2 illustrates the potential avenues for heat exchange in an exercising human and these heat exchange avenues include radiation, conduction, convection, and evaporation.

Radiation

Radiation is heat loss in the form of infrared rays. This involves the transfer of heat from the surface of one object to the surface of another, with no physical contact between them. At rest, radiation is the primary means for dissipating the body's excess heat. At normal room temperature, (i.e., 70 to 77°F or 21 to 25°C), the nude body loses about 60 percent of its excess heat by radiation. This is possible because skin temperature is greater than the temperature of surrounding objects (e.g., walls, floors, furniture, etc.),

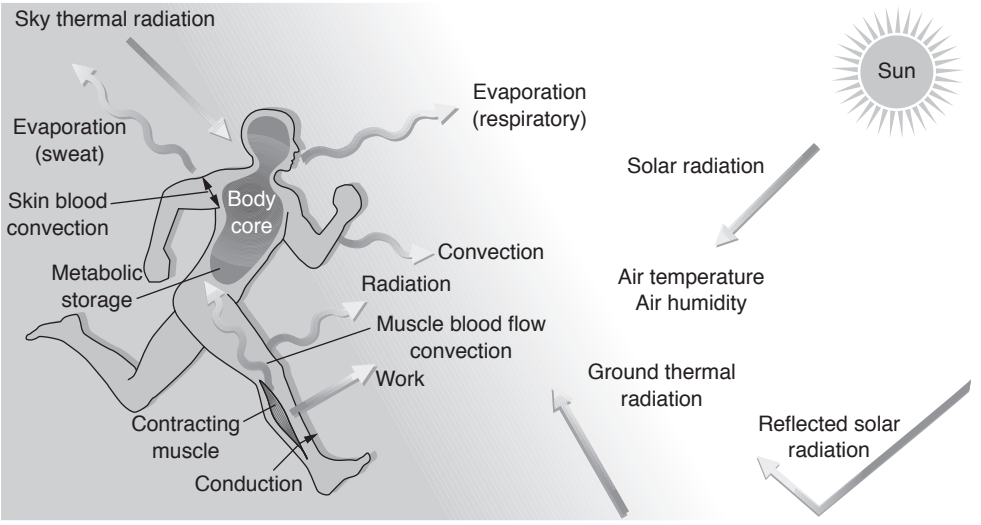


Figure 16.2 Heat exchange avenues and thermoregulation during exercise

and a net loss of body heat occurs due to the thermal gradient. If the temperature of the surrounding objects is greater than that of the skin's surface, the body will experience a net heat gain via radiation. A tremendous amount of heat is received via radiation from exposure to the sun.

Conduction

Conduction is defined as the transfer of heat from the body into the molecules of a cooler object in contact with its surface. In general, the body loses only small amounts of heat due to this process. As an example, heat generated deep in your body can be conducted through adjacent tissues until it reaches the body's surface. It can then be conducted to clothing or a chair that you are sitting on so long as the chair is cooler than the body surface in contact with it. Conversely, when a hot object is pressed against the skin, heat from the object will be transmitted to the skin to warm it.

Convection

Convection is a form of conductive heat loss in which heat is transmitted to either air or water molecules in contact with the body. In other words, it involves moving heat from one place to another by the motion of gas or liquid across the heated surface. Although we are not always aware of it, the air around us is in constant motion. As it circulates around us, passing over the skin, it sweeps away the air molecules that have been warmed by their contact with the skin. The greater the movement of the air or liquid, such as water, the greater the rate of heat dissipation by convection. For example, cycling at high speeds would improve convective cooling when compared to cycling at slow speeds or running. Swimming in cool water also results in convective heat loss. In fact, the water's effectiveness in cooling is about 25 times greater than that of air at the same temperature.

Evaporation

In **evaporation**, heat is transferred from the body to water on the surface of the skin. When this water gains sufficient heat, it is then converted into a gas or water vapor, taking the heat away from the body. Evaporation accounts for about 80 percent of the total heat loss during exercise, but for only 20 to 25 percent of body heat loss at rest. Some evaporation occurs without our being aware of it. This is referred to as insensible water loss and happens wherever body fluid is brought into contact with the external environment, such as in the lungs, the lining of the mouth, and the skin. Insensible water loss removes about 10 percent of the total metabolic heat produced by the body. This heat-loss mechanism is relatively constant, so when the body needs to lose more heat such as during exercise, it becomes insufficient. Instead, as body temperature increases, sweat production increases. As sweat reaches the skin, it is converted from a liquid into a vapor by heat from the skin. Therefore, sweat evaporation becomes increasingly important as body temperature increases. Each liter of sweat that vaporizes transfers 2400 kJ (580 kcal) of heat energy from the body to the environment.

The relative contributions of each of the four heat loss mechanisms are summarized in Table 16.1. The values are simple averages, because individual metabolic heat production varies with body size, body composition, and environmental conditions, such as air current, humidity, and sun exposure. This table depicts some interesting observations. For example, during exercise at moderate to high intensity, heat loss always lags heat production. As intensity of exercise increases, the body will rely more on evaporative heat loss in its effort to maintain a thermal balance.

Table 16.1 Illustration of heat production and heat loss at rest and during exercise of varying intensities

	Rest	*Light-intensity exercise*	*Moderate-intensity exercise*	*High-intensity exercise*
Heat production (kcal hr^{-1})	80	200	350	650
Total heat loss (kcal/hr)	80	200	300	450
Heat balance (kcal hr^{-1})	0	0	+50	+200
Evaporative heat loss (kcal hr^{-1})	25	90	170	350
Evaporative heat loss/total heat loss (%)	31	45	57	78

Sweat rate

Evaporation is our major defense against overheating during exercise, and this is especially the case when the environmental temperature rises. For example, evaporation of sweat can account for as much as 70 percent of total heat loss when exercising in an ambient temperature of 30°C (86°F). During exercise, when body temperature rises above normal, the nervous system stimulates sweat glands to secrete sweat onto the surface of the skin. As sweat evaporates, heat is lost to the environment, which in turn lowers skin temperature. It has been estimated that the sweat rate during exercise has to be at least 1.6 L h^{-1} if all the heat produced is to be dissipated by evaporative heat loss alone. In fact, a much higher sweat rate (~2 L h^{-1}) may be required because some of the sweat rolls off the skin, which has virtually no cooling effect. If we assume that 2 liters of sweat were lost, than this individual would have lost 2 kg (4.4 lb) of body fluids during a 1-hour run; 1 liter of sweat weighs 1 kg or 2.2 lb.

Sweat rate can vary considerably between individuals. Some of the most important non-hereditary factors that determine maximal sweat rates include age, sport, climate, acclimatization, hydration status, and perhaps body fat content. A common estimate of sweat during athletic competition is 1–2 L h^{-1}, but a rate of 2–3 L h^{-1} or more may also occur. In addition, larger individuals would have higher maximal sweat rates during a given exercise task than would smaller individuals.

Factors influencing sweat evaporation

Evaporation of sweat from the skin is dependent on three factors: (1) the temperature and relative humidity; (2) the convective current around the body, and (3) the amount of skin surface exposed to the environment (Nadel 1979). At high environmental temperatures, relative humidity is the most important factor in determining the rate of evaporative heat loss. **Relative humidity** refers to the percentage of water in ambient air at a particular temperature compared with the total quantity of moisture that air can carry. High relative humidity reduces the rate of evaporation. This is because evaporation occurs due to a vapor pressure gradient. That is, in order for evaporative cooling to occur during exercise, the vapor pressure on the skin must be greater than the vapor pressure in the air. At any given temperature, a rise in relative humidity results in increased vapor pressure. Practically speaking, this means that less evaporative cooling occurs during exercise on a hot/humid day. When this occurs, a greater sweat rate is induced, and individuals will dehydrate more rapidly. This dehydration poses further problems for the athlete because progressive dehydration impairs the ability to sweat and, consequently, to thermoregulate. Sweat does not cool the skin; rather, skin cooling occurs only when sweat evaporates.

The amount of skin surface exposed to the environment is another important consideration. This factor may be best explained by using the example of American football. Football uniform and equipment present a considerable barrier to heat dissipation. This can blunt not only evaporative heat loss, but also heat loss through radiation and convection. Even with loose-fitting porous jerseys, the wrappings, padding, helmet, and other objects of armor effectively seal off nearly 50 percent of the body's surface from the benefits of evaporative cooling, not to mention the heat stress from a hot artificial playing surface. Heat load can increase even further for those who are larger in size, such as offensive and defensive linemen. This is because they possess a smaller body surface area-to-body mass ratio and a higher percent body fat than players in other positions.

Role of circulation in heat dissipation

The circulatory system serves as the "driving force" to maintain thermal balance. In hot weather, heart rate and blood flow from the heart increases while superficial arterial and venous blood-vessels dilate to divert warm blood to the body's shell. This manifests as a flushed or reddened face on a hot day or during vigorous exercise. Under normal condition, skin receives no more than 10 percent of cardiac output. However, with extreme heat stress, as much as 25 percent of the cardiac output passes through the skin, raising skin temperature that can facilitate heat loss via radiation. The down side of this circulatory adjustment is that it may hamper blood and oxygen supply to the working muscle as well as possibly reducing **stroke volume**, the amount of blood ejected by the heart per beat, and increasing heart rate. To state it simply: when exercising in the heat, skin and working muscle will compete for blood.

Regulation of fluid and electrolyte balance in the body

The three main organs that regulate fluid and electrolyte balance are the brain, the adrenal glands, and the kidneys. These three organs work together via a negative feedback manner in making sure that the body's fluid and electrolytes remain balanced. For example, a decrease in fluid volume triggers **thirst** sensation in the hypothalamus and causes the posterior pituitary gland to release antidiuretic hormones, resulting in the kidneys retaining water. On the other hand, a decrease in blood sodium concentration stimulates the adrenal cortex to secrete the hormone aldosterone, which instructs the kidneys to retain more sodium.

Role of hypothalamus

A constant supply of water without excess or deficiency is needed in the body. Water intake must be equal to water loss in order to maintain water balance. The desire to drink, or thirst, is triggered by the thirst center in the brain, particularly the hypothalamus, when it senses a decrease in blood volume and an increase in the concentration of dissolved substances (i.e., sodium) in the blood. A decrease in the amount of water in the blood also decreases saliva secretion resulting in a dry mouth. Together, signals from the brain and a dry mouth motivate the consumption of fluid.

Thirst drives a person to seek water, but it often lags behind the body's needs. For example, it has been found that athletes exercising in hot weather lose water rapidly but do not experience intense thirst until they have lost so much body water that their performance is compromised. For this reason, athletes should carefully monitor fluid status – they should weigh themselves before and after training sessions to determine their rate

of water loss and, thus, their water needs. A person suffering fever, vomiting, or diarrhea may also be losing water rapidly and the thirst mechanism may not be adequate to replace the fluid. In children and the elderly, the thirst mechanism can also become less sensitive or unreliable, so an individual may not be thirsty even though body water is depleted. Even when a person does respond to thirst, the amount of fluid consumed can be insufficient to replace the water loss because thirst is quenched almost as soon as fluid is consumed and long before water balance is restored.

Condition of dehydration

When too much water is lost from the body and not replaced, **dehydration** or hypohydration develops. Dehydration occurs when the loss of body water is great enough for blood volume to decrease, thereby reducing the ability to deliver oxygen and nutrients to the cells and to remove waste products. A first sign of dehydration is thirst, the signal that the body has already lost some fluid. If a person is unable to obtain fluid or, as in many elderly people, fails to perceive the thirst message, the symptoms of dehydration may progress rapidly from thirst to weakness, exhaustion, and delirium, and end in death if not corrected. Early symptoms of dehydration (i.e., a body water loss of ~2 percent of body weight) include headache, fatigue, loss of appetite, dry eyes and mouth, and dark-colored urine. A loss of 5 to 6 percent of body water may cause nausea and difficulty concentrating. Confusion and disorientation may occur when water loss approaches 7 to 8 percent. A loss of about 9 to 10 percent may result in exhaustion, collapse, and death (Table 16.2).

Action of the kidneys

Once the body experiences a shortage of available water, it increases fluid conservation. Two hormones that participate in this process are the **anti-diuretic hormone** and **aldosterone**. The posterior pituitary gland releases the anti-diuretic hormone to force the kidneys to conserve water and electrolytes. The kidneys respond by reducing urine flow. At the same time, as fluid volume decreases in the bloodstream, blood pressure falls. This eventually triggers the release of the hormone aldosterone, which signals the

Table 16.2 Signs and symptoms of dehydration

Body weight loss (%)	*Symptoms*
1–2	Thirst, fatigue, weakness, discomfort, loss of appetite, impaired physical and cognitive performance
3–4	Decreasing blood volume and urine output, dry mouth, flushed skin, impatient, nausea, apathy, declining physical performance
5–6	Headache, difficulty concentrating, irritability, impaired temperature regulation, increased pulse and breathing rate, sleepiness
7–8	Dizziness, labored breathing with exertion, loss of balance, disorientation, mental confusion, indistinct speech
9–10	Muscle spasm, impaired circulation, hypotension, delirium, renal failure, exhaustion, collapse

Note
The onset and severity of symptoms at various percentages of body weight lost depend on the intensity of the activity, fitness level, degree of acclimation, and environmental temperature and humidity

kidneys to retain more sodium and, in turn, more water. Alcohol inhibits the action of the anti-diuretic hormone. One reason people feel so weak the day after heavy drinking is that they are dehydrated. Even though they may have consumed a lot of liquid in their drinks, they have lost even more liquid because alcohol has inhibited the anti-diuretic hormone. Despite mechanisms that work to reduce water loss via the kidneys, fluid continues to be lost via the feces, skin, and lungs. Those losses must be replaced. In addition, there is a limit to how concentrated urine can become. Eventually, if fluid is not consumed, the body can still suffer the ill-effects of dehydration despite the action of these two regulatory hormones.

Water intoxication, on the other hand, is rare but may occur with excessive water ingestion and kidney disorders that reduce urine production. The symptoms may include confusion, convulsions, and even death in extreme cases. Excessive water ingestion contributing to this dangerous condition is known as **hyponatremia**. This water intoxication is mainly seen in endurance athletes and has been associated with symptoms such as nausea and vomiting, headache, confusion, muscle weakness or cramps, and, if severe, seizure and coma.

Effect of dehydration on exercise performance

As discussed earlier, dehydration is defined as the excessive loss of body fluid. It reflects an imbalance that fluid intake does not replenish water loss from the normally hydrated state. Dehydration is one of the most significant nutritional factors that can reduce physical performance. All too often, endurance athletes and athletes participating in sports associated with heavy sweating, such as soccer, field hockey, lacrosse, tennis, and American football, experience at least some level of dehydration during training and competitions. Other athletes such as wrestlers, boxers, body builders, and fitness competitors sometimes deliberately restrict their fluid consumption prior to a competition to qualify for a lower weight category or to enhance aesthetic presentation. This latter approach is referred to as voluntary dehydration, and is generally discouraged due to its potential to cause health problems (Oppliger *et al.* 1996).

Voluntary dehydration

Athletes participating in sports such as wrestling, lightweight crew, judo, and boxing often attempt to dehydrate in order to "make weight" and compete within a lower weight class. The term "hypohydration" is often used to describe voluntary efforts to reduce body water levels. Some of the commonly used techniques for voluntary dehydration include exercise-induced sweating, thermal-induced sweating such as the use of saunas, use of diuretics to increase urine losses, and reduced intake of fluids and foods. As mentioned earlier, reduction of body water by 1 liter is equivalent to 1 kg (2.2 lb). These athletes then attempt to rehydrate between the weigh-in qualification and the actual competition in order to "size up."

Much of the research with voluntary dehydration has been conducted with wrestlers. Evaluation criteria have emphasized factors such as muscular strength, power, and endurance and anaerobic activities designed to mimic wrestling. Controversies seem to exist as to the impact of voluntary dehydration upon muscular strength and endurance and ultra-short-term performance. Many studies conducted in this regard suggest that hypohydration, even up to levels of 8 percent of body weight, will not affect physical performance in events involving brief, intense muscular effort. For example, Greiw *et al.* (1998) reported that 4 percent reduction in body weight had no effect on isometric muscle strength or endurance. On the other hand, Schoffstall *et al.* (2001) reported that

dehydration resulting in approximately 1.5 percent loss of body mass adversely affected bench press 1-repetition maximum performance, but these adverse effects seem to disappear after a 2-hour rest period and water consumption. The adverse effects on strength are not consistent, but anaerobic tasks lasting longer than 20 seconds have been impaired when subjects were hypohydrated. For example, Montain *et al.* (1998) observed a 15 percent reduction in time of repeated knee extension to exhaustion following a 4 percent decrease in body weight as water. This reduced performance through hypohydration was attributed to a loss of potassium from muscle and higher muscle temperature during exercise.

Research studies are more consistent in demonstrating a negative impact of voluntary dehydration upon aerobic, endurance performance. Dehydration induced by hypohydration practices may have a different influence on physical performance than involuntary or exercise-induced dehydration in that the effects of dehydration may be experienced at the onset of physical activity. This can result in reduced performance even in shorter duration sports. It was reported that when runners performed 1.5-, 5-, and 10-km runs in either a well-hydrated state or a partially hypohydrated state (2 percent reduction in body weight as water), their running speed was significantly lower at distances of 5- and 10-km, and a similar trend was observed during a 1.5-km run (Sawka and Pandolf 1990). Maxwell *et al.* (1999) also reported a reduction in performance in 20-second sprinting bouts separated by 100 seconds of rest in a dehydrated state.

In addition to a potential to reduce physical performance, hypohydration can influence the general health of individuals. As involuntary dehydration, hypohydration-induced fluid loss may compromise thermal regulation during exercise in hot environments and causes cardiovascular complications. Deaths linked to hypohydration have been reported in wrestlers who experienced kidney and heart failure while working out in a hot environment and being dehydrated (Oppliger *et al.* 1996). Coaches and athletes should be well educated about the dangers and symptoms of severe dehydration and electrolyte imbalances.

Involuntary or exercise-induced dehydration

Body water loss is rapid during exercise in the heat and is often not matched by an athlete's fluid consumption. This involuntary dehydration is most common during prolonged physical activity, particularly under warm, humid conditions. Exercise performance is impaired when an individual is dehydrated by as little as 2 percent of body weight. Losses in excess of 5 percent of body weight can decrease the capacity for work by about 30 percent (Maughan 1991, Sawka and Pandolf 1990). Even in cool laboratory conditions, maximal aerobic power (VO_2max) decreases by about 5 percent when subjects experience fluid losses equivalent to 3 percent of body mass or more (Pichan *et al.* 1988). In hot conditions, similar water deficits can cause a greater decrease in VO_2max. The dehydration-induced impairment in exercise performance is much more likely in hot environments than in cool conditions, which implies that altered thermoregulation is an important factor responsible for the reduced exercise performance associated with dehydration.

The negative impact of dehydration upon endurance performance seems to also occur when exercise is performed at lower intensities. One study investigated the endurance capacity of eight subjects to perform treadmill walking at 25 percent VO_2max for 140 minutes in very hot and dry conditions (49°C or 120°F and 20 percent relative humidity) (Sawka *et al.* 1985). All subjects were able to complete 140 minutes of walking when euhydrated and 3 percent dehydrated. But when dehydrated by 7 percent, six subjects stopped walking after an average of only 64 minutes. Therefore, even for relatively

mild exercise, dehydration can bring about early fatigue from heat stress. In another study, this same research group had subjects walk to exhaustion at 47 percent VO_2max in the same environmental conditions as their previous study (Sawka *et al.* 1992). Comparisons were made between subjects who were euhydrated and those who were dehydrated to a loss of 8 percent of total body water. Dehydration reduced endurance time from 121 minutes to 55 minutes. In this study, it was also found that rectal temperature at exhaustion was about 0.4°C (0.7°F) lower in the dehydration state, which suggests that dehydration may reduce the core temperature a person can tolerate.

The reasons dehydration has an adverse effect on exercise performance may be attributed mainly to factors that are cardiovascular and metabolic in origin. Fluid flux from the plasma during the early phase of endurance exercise is important to support efficient sweating. If sweating is mild or if fluid consumption is adequate, plasma volume can be stabilized during exercise. However, when sweating is heavy and is uncompensated by fluid consumption, plasma volume will decrease. This can reduce stroke volume. As a result, heart rate is accelerated in order to maintain a given cardiac output. When plasma is further reduced, heart rate maximizes and cardiac output peaks. Cardiac output begins to decrease with further reductions in plasma volume.

Hence, a reduced maximal cardiac output (i.e., the highest pumping capacity of the heart that can be achieved during exercise) is the most likely physiological mechanism by which dehydration decreases a person's VO_2max and impairs work capacity in fatiguing exercise of an incremental nature, as reported in previous studies. This is because reduced cardiac output will deliver less blood and nutrients to working muscle. When blood flow to working muscle is decreased, there is also reduced ability to transport heat and waste products such as lactic acid away from the muscle. In addition to its negative impact upon stroke volume and heart rate, a decreased plasma volume also increases blood thickness (viscosity), which is a measure of internal resistance to blood flow. As part of thermoregulation discussed earlier, there could be a further reduction in blood flow to working muscle due to the dilation of skin bloodvessels aimed to dissipate heat.

Dehydration can reduce blood flow to working muscle and influence substrate utilization. This may lead to an increased use of carbohydrate and reduced use of fat. The larger rise in core temperature during exercise in the dehydrated state is associated with a greater catecholamine response, which may lead to increased rates of glycogen breakdown. Together, these responses will in turn increase the production of lactic acid and at the same time exhaust glycogen stores more quickly. González-Alonso *et al.* (1999) evaluated cyclists riding at 60 percent VO_2max on the two different occasions, once while they were provided adequate fluid to prevent dehydration and another time when they were dehydrated that resulted in a reduction in body weight by 3.9 percent. When the cyclists were not provided with fluids, blood flow to their legs was lower and glycogen breakdown and lactate content were greater during later stages of exercise in comparison to when they were provided with sufficient fluids.

Other factors associated with dehydration may also contribute to a decrement in exercise performance. Disturbed fluid and electrolyte balance in the muscle cells may affect neuromuscular function and the energy transformation process, while adverse effects of hyperthermia on mental processes may contribute to central fatigue. It has been reported that 1 to 2 percent dehydration can significantly impair cognitive function (Armstrong and Epstein 1999). Dehydration can also cause gastrointestinal symptoms, such as nausea, vomiting, bloating, cramps, diarrhea, and bleeding, many of which could impair performance if severe enough.

Fluid replacement strategies

Adequate fluid replacement during exercise sustains the potential for evaporative cooling and helps maintain or restore plasma volume to near pre-exercise levels. As compared to dehydration, adequate hydration will help decrease fluid loss, reduce cardiovascular strain, enhance performance, and prevent heat-related illness. For decades, hydration status was not recognized as important during activity. Some coaches and athletes still believe water consumption hinders performance. Today, hydration status is viewed as a crucial component of successful performance.

General hydration and rehydration guidelines

Athletes must be fully hydrated before they train or compete because the body cannot adapt to dehydration. An adequately hydrated state can be assured by a high fluid intake in the last few days before a competition. A useful check is to observe the volume and color of the urine. Voiding small volumes of dark-yellow urine with a strong odor provides a qualitative indication of inadequate hydration. Well-hydrated individuals typically produce urine in large volumes, light in color, and without a strong smell. Observation of a urine sample cannot be reliably used if the athlete is taking vitamin supplements, as some excreted water-soluble B vitamins add a yellowish hue to the urine. A more definite indication of hydration status is obtained by measuring urine **osmolality**. Osmolarity is the measure of solute concentration of a solution. A urine osmolality of over 900 mOsmol/kg indicates that the athlete is relatively dehydrated, whereas values of 100 to 300 mOsmol/kg indicate that the athlete is well hydrated. Measuring the athlete's body weight after the rising and voiding each morning may also prove useful. Some coaches require athletes to weigh in before and after practice to monitor fluid balance. Remember: each 1 kg (2.2 lb.) weight loss represents 1 L (35 fl oz) of dehydration. A sudden drop in body mass on any given day is likely to indicate dehydration.

Athletes should be urged to rehydrate themselves because depending on their own thirst sensation to trigger water intake is not reliable. Ideally, athletes should consume enough fluids to make body weight remain constant before and after exercise. Older individuals generally require a longer time to achieve rehydration after dehydration (Kenney and Chiu 2001). If rehydration were left entirely to a person's thirst, it could take several days after severe dehydration to re-establish the fluid balance. Therefore, athletes should become accustomed to consuming fluid at regular intervals with and without thirst during training sessions so that they do not develop discomfort during competitions. It is recommended that approximately 500 ml fluid be consumed 2 hours before exercise, followed by another 500 ml about 15 minutes before prolonged exercise (Association; Dietitians of Canada; American College of Sports Medicine 2009). In a hot and humid environment, frequent consumption (every 15 to 20 minutes) of small amounts (120 to 180 ml) of fluid is recommended during exercise (American Dietetic Association; Dietitians of Canada; American College of Sports Medicine 2009).

Until recently, athletes were generally encouraged to consume a volume of fluid equivalent to their sweat loss incurred during exercise to adequately rehydrate in the post-exercise recovery period. In other words, they were to consume about 1 L of fluid for every kg lost during exercise. However, this amount is considered insufficient because it does not take into account the urine loss associated with beverage consumption. In this context, it is suggested that ingestion of 150 percent or more of weight loss (i.e., consume 1.5 L of fluid for every kg lost) during recovery would be adequate to achieve a desirable hydration status following exercise (Sawka *et al.* 2007, Shirreffs and Maughan 2000). This 50 percent "extra" water accounts for that portion of ingested water lost in urine.

Composition of replacement fluid

In the 1960s, Robert Code, a scientist/physician working at the University of Florida, developed an oral fluid replacement that was designed for athletes to restore some of the nutrients lost in sweat. This product was eventually marketed as Gatorade and was the first of many **glucose electrolyte solutions** and later, **glucose polymer solutions** to appear as a sports drink on the market. The glucose electrolyte solutions were the first commercial fluid replacement preparations designed to replace fluid and carbohydrate. Common brands today include All-Sport, Gatorade, and PowerAde. Other than water, the major ingredients in these solutions are carbohydrates usually in various combinations of glucose, glucose polymers, sucrose, or fructose, and some of the major electrolytes. The sugar content ranges from 5 to 10 percent depending on the brand. The major electrolytes include sodium, chloride, potassium, and phosphorous. Some brands may also include other substances such as vitamin Bs, vitamin C, calcium, magnesium, branched-chain amino acids, caffeine, as well as artificial coloring and flavoring (Table 16.3). Electrolytes such as sodium, chloride, and potassium play a critical role in the rehydration process. It has been demonstrated that plasma volume can be fully restored if beverages contain sufficient sodium chloride (i.e., 450 mg L^{-1}) (Nose *et al.* 1988). A small amount of potassium also enhances water retention in the intracellular space and may diminish extra potassium loss that results from sodium retention by the kidneys.

Obviously, one of the goals of researchers has been to develop a fluid that will help replace carbohydrate during exercise in the heat without sacrificing water absorption. In general, as osmolarity or solute concentration of a solution increases, fluid absorption decreases. Glucose polymer solutions are designed to provide carbohydrate while decreasing the osmotic concentration of the solution, thus helping with fluid absorption. **Maltodextrin** is a glucose polymer that exerts lesser osmotic effects compared with glucose, and is thus used in a variety of sports drinks as the source of carbohydrate. It is the main ingredient in a few commercial brands, such as Ultima. Other sports drinks combine maltodextrins with glucose, sucrose, and fructose. It is believed that sports drinks which contain maltodextrins will facilitate fluid absorption while maintaining an adequate carbohydrate supply. Table 16.3 compares the compositions of several commercially available sports drinks that are commonly chosen by athletes during training and competition.

How much carbohydrate a replacement fluid has can affect **gastric emptying**, which is another important consideration for effective rehydration. Fluid ingestion during exercise supplies exogenous fuel substrate, such as carbohydrate, as well as helping maintain plasma volume and preventing dehydration. However, the availability of ingested fluids may be limited by the rate of gastric emptying or intestinal absorption. Gastric emptying refers to the process by which food leaves the stomach and enters the duodenum. High gastric emptying rates are advisable for sports drinks in order to maximize fluid absorption. Gastric emptying of fluids is slower by the addition of carbohydrate or other macronutrients that increase the osmolarity of the solution ingested. Therefore, when glucose concentration in the fluid ingested increases, the rate of fluid volume delivery to the small intestine decreases despite the fact that glucose delivery may increase.

Due to the fact that adding carbohydrate to a replacement fluid has the potential to hamper gastric emptying and thus fluid absorption, one should be cautious in choosing a sports drink. In cool environments, where substrate provision to maintain endurance performance is more important, a concentrated solution containing large amounts of glucose is recommended. To avoid the limitation imposed by the rate of gastric emptying, the osmolarity of the beverage should be minimized by using glucose in the form of glucose polymers. The current evidence suggests the use of a 5 to 10 percent

Table 16.3 Composition of commonly used carbohydrate beverages

Beverage	*Energy (kcal)*	*CHO (g)*	*CHO sources*	*Sodium (mg)*	*Potassium (mg)*	*Caffeine (mg)*
Gatorade (thirst quencher)	50	14	Sucrose, glucose, fructose	110	25	0
Gatorade (endurance formula)	50	14	Sucrose, glucose, fructose	200	90	0
All sports	60	16	HFCS	55	50	0
PowerAde	64	17	HFCS, maltodextrin	53	32	0
Accelerade (PacificHealth Laboratories)	80	14	Sucrose, fructose, maltodextrin	130	43	0
Vitamin water	50	13	Fructose	0	0	0
Coca Cola	97	27	HFCS	33	0	23
Pepsi	100	27	HFCS, glucose	25	10	25
Mountain Dew	110	31	HFCS, orange juice concentrate	50	0	37
Orange juice	110	27	Sucrose, fructose, glucose	15	450	0
Proper (fitness water)	10	3	Sucrose syrup	35	0	0

Source: data gathered from product labels and sources provided by manufacturers.

Note
HFCS=High-fructose corn syrup.

solution of multiple forms of carbohydrate including glucose polymers and maltodextrin. When dehydration or hyperthermia is the major threat to performance, water replacement is the primary consideration. In this case, a more diluted solution that contains glucose in the form of maltodextrin is a more appropriate choice. In very prolonged exercise in the heat with heavy sweat loss, such as ultramarathons, electrolyte replacement may be essential to prevent heat injury.

Drinking plain water is not a good choice for rehydration unless it is used in conjunction with solid foods. Drinking too much plain water can dilute the electrolyte content (mainly sodium) in the blood, thereby decreasing plasma osmolality. This will then stimulate urine production and blunt the drive to drink, both of which can delay the rehydration process. Maintaining a relatively higher plasma sodium concentration will promote the retention of ingested fluids, making body fluid balance more quickly accomplished. Use of too much plain water can also increase the risk of developing a condition of hyponatremia or water intoxication.

Hyperhydration

Hyperhydration refers to an attempt to begin an exercise bout with a slight surplus of body water. The advantage of beginning exercise when hyperhydrated is that it will delay or eliminate the onset of hypohydration if one fails to completely replace sweat loss during exercise. This will allow for a greater volume of sweat loss prior to a reduction in performance. In addition, beginning exercise with a slightly expanded plasma volume may provide a necessary buffer against detrimental reduction in plasma volume typically experienced during sustained vigorous activity. Hyperhydration may benefit athletes during prolonged exercise in a hot environment. Athletes competing in intermittently high-intensity sports for a couple of hours, with less opportunity to consume adequate fluids, may also consider this approach. The sports usually associated with hyperhydration include distance running, triathlon, soccer, and tennis. Disadvantages of hyperhydration include increased body weight, urine production, and incidence of gastrointestinal discomfort. Therefore, the decision to go forward with the hyperhydration procedure must be made based on whether the advantages of hyperhydration are considered superior to its temporary disadvantages.

Research generally supports the notion that hyperhydration reduces thermal and cardiovascular strain of exercise (Lamb and Shehata 1999). However, there is insufficient evidence to support the claim that pre-exercise hyperhydration improves exercise performance (Lamb and Shehata 1999, Sawka *et al.* 2001). Hyperhydration may increase water content in the body, but the effect was reported to be short-lived. Much of the fluid overload is rapidly excreted. This could raise a question as to whether water storage is still significantly higher at the onset of a competition. Clearly, more research is needed to substantiate this hydration approach. Pre-exercise hyperhydration does not replace the need to continually replenish fluid during exercise because during intense endurance exercise in heat fluid loss usually outpaces fluid intake. On the other hand, hyperhydration is unnecessary when euhydration is maintained during exercise. Obviously, the hyperhydration procedure to be followed before key races must first have been thoroughly tested during specific training or low-key races.

Traditionally, the fluid of choice for hyperhydration has been water, but over the past five to six years an increasing number of athletes are choosing to hyperhydrate exclusively with a glycerol solution. Glycerol is a three-carbon molecule formed mainly from carbohydrate and fat metabolism. Why glycerol? The kidneys are extremely efficient at rapidly excreting the excess water in water-induced hyperhydration, so the increase in total body water is typically short-lived. But when an athlete hyperhydrates with glycerol, its osmotic

(soaking) property significantly reduces urine production and therefore increases water storage. It has been reported that using a glycerol solution can make the hyperhydration period last approximately twice as long as using water. Proponents of glycerol argue that because its use allows an athlete to maintain an enhanced fluid reservoir for a longer period of time, cardiovascular and thermoregulatory functions will be better preserved during exercise, thereby improving performance. This role of glycerol is also discussed in Chapter 11.

Overall recommendations

Adequate fluid replacement sustains the potential for evaporative cooling during exercise. Properly scheduling fluid replacement maintains plasma volume so that circulation and sweating operate optimally. Strictly following an adequate water replacement schedule prevents dehydration and its related consequences, and promotes the health, safety, and optimal performance of people who participate in regular physical activity and sports. The following are more specific recommendations made by the American College of Sports Medicine on the amount and composition of fluids that should be ingested before, during, and after athletic competitions:

- Slowly drink 5 to 7 mL kg^{-1} at least 4 hours before the exercise task and then 3 to 5 mL kg^{-1} about 2 hours before the event; this will allow sufficient time for urine output to return toward normal before starting the event. Consuming beverages with sodium and/or salted snacks or sodium-containing foods at meals will help stimulate thirst and retain the consumed fluids.
- The goal of drinking during exercise is to prevent excessive dehydration and dramatic changes in electrolyte balance to avert compromised exercise performance. The amount and rate of fluid replacement depends on the individual sweating rate, exercise duration, and opportunities to drink. Individuals should develop customized fluid replacement programs to achieve this goal.
- Ingested fluids should be cooler than ambient temperature (i.e., 15 to 22°C or 59 to 72°F), flavored to enhance palatability and fluid replacement, and readily available in ample volume.
- During exercise lasting longer than one hour, carbohydrate should be consumed at a rate of ~30–60 g h^{-1} to meet carbohydrate needs and delay fatigue; this can be achieved by drinking 600 to 1200 ml h^{-1} of solutions containing 4 to 8 percent carbohydrate. Ingested beverages should also contain sodium (i.e., 500 to 700 mg L^{-1}) to maintain plasma osmolality, promote fluid retention, and prevent hyponatremia.
- After exercise, individuals needing rapid and complete recovery from excessive dehydration should drink ~1.5 L of fluid for each kilogram of body weight lost. Consuming beverages and snacks with sodium will help expedite rapid and complete recovery by stimulating thirst and fluid retention.

Heat injuries

One of the most serious threats to the performance and health of physically active individuals is heat injuries, or heat illness. An early report indicates that heat-related injuries and illness cause 240 deaths annually, often in athletes (Barrow and Clark 1998). Heat injury is most common during exhaustive exercise in a hot, humid environment, particularly if the athlete is dehydrated. These problems affect not only highly trained athletes, but also less well-trained sports participants. In fact, those who are less well trained or overweight and poorly conditioned are more prone to heat injuries because they have less effective thermoregulation, work less economically, and use more carbohydrate for

muscular work. From the perspective of health and safety, it is far easier to prevent heat injury than to remedy it. However, if one fails to pay attention to the normal signs of heat stress, such as thirst, tiredness, lightheadedness, and visual disturbances, the body's internal organs, especially the cardiovascular system, may lose their ability to further compensate, thereby triggering a series of disabling complications, some of which can have long-term consequences or be fatal.

In general, heat injuries result from chronic exposure to the combination of external heat stress and the inability to dissipate metabolically generated heat. Heat injuries, in order of increasing severity, include heat cramps, heat exhaustion, and exertional heat-stroke. The following sections attempt to discuss each level of heat injuries separately, but readers must be aware that no clear-cut demarcation exists between these disorders because symptoms usually overlap. As shown in Figure 16.3, it is often the cumulative effects of multiple adverse stimuli that produce heat-related injuries.

Heat cramps

Heat cramps, the least serious of the three heat disorders, are characterized by severe involuntary muscle spasms that occur during and after intense physical activity. They involve primarily the muscles that are most heavily used during exercise, although cramps may also occur in the muscles of the abdomen. This disorder is most likely brought on by the electrolyte losses and dehydration that accompany high rates of sweating (Figure 16.3). Those who often experience cramps tend to have high sweat rates and/or high sweat sodium concentrations. With heat cramps, body temperature does

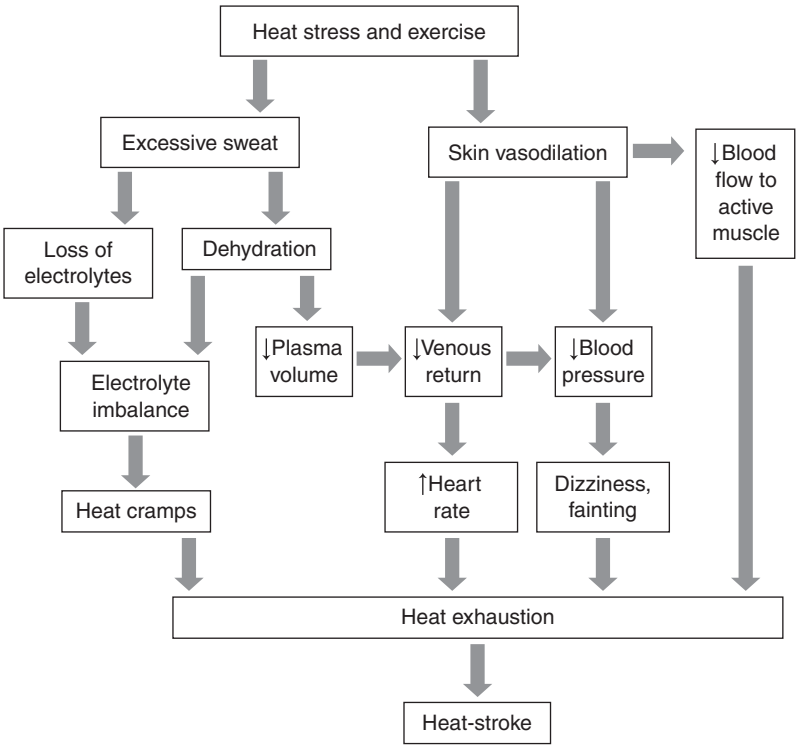


Figure 16.3 Flow chart for the causes and progression of heat injuries

not necessarily increase. Heat cramps are treated by moving the stricken individual to a cooler location and administering fluids or a saline solution. One can prevent this heat-related disorder by consuming a relatively large quantity of fluids rich in electrolytes and/or increasing daily salt intake moderately (e.g., adding salt to foods at mealtimes) several days before heat stress.

Heat exhaustion

Heat exhaustion is the most common heat illness among physically active individuals, and usually develops in those who are dehydrated, untrained, and unacclimatized. It is often seen during the first summer heatwave or first hard training session on a hot day. Heat exhaustion is typically accompanied by such symptoms as extreme fatigue, breathlessness, dizziness, vomiting, fainting, cold and clammy or hot and dry skin, low blood pressure, and a weak, rapid pulse. This more serious condition is caused by the cardiovascular system's inability to adjust compounded by the depletion of extracellular fluid including plasma from excessive sweating. Blood pools in the dilated peripheral vessels. This drastically reduces the central blood volume required to maintain cardiac output. During exercise in heat, your active muscles and your skin, through which excess heat is lost, compete for a share of your total blood volume. Heat exhaustion results when these simultaneous demands are not met.

With heat exhaustion, the thermoregulatory mechanisms are functioning but cannot dissipate heat quickly enough because insufficient blood volume is available to allow adequate distribution to the skin. Both stroke volume and blood pressure also fall due to a reduced central blood volume. Consequently, heart rate increases in an effort to maintain cardiac output (Figure 16.3). As central blood volume and pressure continue to decrease, sympathetic nervous activity increases and the skin's blood-vessels constrict. A more powerful constriction of the blood-vessels supplying the abdominal organs leads to cellular hypoxia in the region of the gastrointestinal tract, liver, and kidneys. Cellular hypoxia leads to the production of reactive oxygen species including nitric oxide (NO). NO is a potent blood-vessel dilator and its production may be viewed as protective, helping conserve some blood flow through the capillary beds of the abdominal organs. However, increased levels of NO contribute to a further reduction in blood pressure.

Treatment for victims of heat exhaustion involves rest in a cooler environment with their feet elevated. If the person is conscious, administration of salt water is recommended. If the person is unconscious, it is recommended that saline solution be administered intravenously. If heat exhaustion is allowed to progress, it can deteriorate into heat-stroke.

Heat-stroke

Heat-stroke is a form of hyperthermia, an abnormally elevated body temperature with accompanying physical and neurological symptoms. It is the escalation of two other heat-related health problems: heat cramps and heat exhaustion (Figure 16.3). Unlike heat cramps and heat exhaustion that are less severe, heat-stroke is a life-threatening heat disorder that requires immediate medical attention. Heat-stroke is caused by failure of the body's thermoregulatory mechanisms. With thermoregulatory failure, sweating usually ceases, the skin becomes hot and dry, body temperature rises to 40.5°C (105°F) or higher, and the circulatory system becomes excessively strained. Heat-stroke is characterized by an increase in body temperature to a value exceeding 40°C (104°F), cessation of sweating, hot, dry, and flushed skin, rapid pulse and breathing, muscle cramps or weakness, and confusion and unconsciousness.

Sometimes a person experiences symptoms of heat exhaustion before progressing to heat-stroke. As mentioned earlier, symptoms of heat exhaustion may include nausea, vomiting, fatigue, weakness, headache, muscle cramps and aches, and dizziness. These signs and symptoms are milder than those of heat-stroke, and you can prevent heat-stroke if you receive medical attention or take self-care steps as soon as you notice problems. If these symptoms are left unnoticed or untreated, these relatively milder symptoms can progress to result in heat-stroke, which can be fatal from circulatory collapse, oxidative damage, systemic inflammatory response, and damage to the central nervous system. Heat-stroke may also lead to **rhabdomyolysis**, a condition in which damaged tissue leaks its contents into the blood, eventually leading to kidney damage and possible death.

The populations most susceptible to heat-stroke are infants, the elderly (often with associated heart diseases, lung diseases, or kidney diseases), athletes, and outdoor workers physically exerting themselves in the sun for an extended period of time. For athletes, heat-stroke is a problem associated not only with extreme environmental conditions. Earlier studies have reported rectal temperatures above 40.5°C (105°F) in marathon runners who successfully competed races conducted under moderate thermal conditions (e.g., 21°C or 70°F and 30 percent relative humidity). Athletes who are on weight loss supplements, such as ephedrine, are more prone to developing this more severe heat injury, as most weight loss products impose extra strain on the cardiovascular system.

Treatment involves rapid mechanical cooling along with standard resuscitation measures. The body temperature must be lowered immediately. The victim should be moved to a cool area (e.g., indoors or at least into the shade) and placed into the recovery position to ensure that the airway remains open. Active cooling methods may be used and these methods include applying cool or tepid water to the skin, fanning the victim to promote evaporation of water, and placing ice-packs under the armpits and groin. Immersion in very cold water is counterproductive, as it causes vasoconstriction in the skin and thereby prevents heat from escaping the body core. Hydration is of paramount importance in cooling the victim. This is achieved by drinking water if the victim is conscious. However, if the victim is unconscious or unable to tolerate oral fluids, intravenous hydration is necessary. These cooling efforts should be continued until the body temperature drops to ~38°C (100°F). Of course, always notify emergency services immediately.

Factors influencing heat tolerance

Who may be more subject to heat injuries? How can we prepare for prolonged activity in the heat? Does training in the heat make us more tolerant of thermal stress? Many studies have investigated these questions. To date, a number of predisposing factors have been identified to be associated with heat injury and they include gender, age, percent body fat, level of fitness, previous history of heat injury, and degree of acclimatization.

Level of fitness

One of the major factors contributing to heat injuries is poor physical fitness. Using male Marine Corps recruits as subjects, Gardner *et al.* (1996) observed that the risk for developing heat illness increased with increase in time to complete a 1.5-mile run conducted during the first week of basic training. For a physical fit individual, a given physical task will represent a lower percentage of his or her VO_2max. In addition, those who are physically fit usually have augmented circulatory function that can allow a more

effective heat transfer from the core to the skin. Therefore, the better the physical fitness, the better the heat tolerance to a given heat stress. However, it is a mistake to believe that athletes are immune to any heat injury. There have been reports on heat-related deaths in some of the elite athletes. These incidences were often related to the unsafe training practices or attempts to reduce body weight for competition through sweating in a hot environment. For example, one of the NCAA Division I wrestlers who died was wearing a rubber suit while riding a stationary bicycle in a steam-filled shower.

Gender

A distinct sex difference in thermoregulation exists for sweating. Women possess more heat-activated sweat glands per unit of skin area than men, yet they sweat less. Women begin to sweat at higher skin and core temperatures, which means that they do not sweat as early as men during heat exposure or exercise. Despite a lower sweat output, women show similar heat tolerance as compared to men of equal aerobic fitness. For example, comparing male and female runners of a comparable level of fitness, Arngrímsson *et al.* (2004) found that heat-induced reduction in VO_2max and physical performance were identical between men and women. This similarity may be in part attributable to the fact that, although women sweat comparatively less, they have a greater evaporative efficiency than men (Kaciuba-Uscilko and Grucza 2001). This may be because women possess a relatively large body surface area-to-body mass ratio, a favorable dimensional characteristic for heat dissipation. In other words, under identical conditions of heat exposure, women cool at a faster rate than men through a smaller body mass across a relatively larger surface area. The similarity in heat tolerance between men and women of equal aerobic fitness may also be ascribed to the fact that women rely more on circulatory cooling, whereas a greater evaporative cooling occurs in men. This gender difference may impose a greater circulatory strain (i.e., a greater increase in heart rate) in women than in men. Nevertheless, less sweat production to maintain thermal balance protects women from dehydration during exercise in the heat.

Age

Does aging impair one's ability to thermoregulate and exercise in the heat? Some of the earlier evidence suggests that the ability to exercise in the heat decreases with advancing age (Dill and Consolazio 1962). However, more recent studies reported that older and young men with a similar level of training show little difference in thermoregulation during exercise (Pandolf *et al.* 1988, Thomas *et al.* 1999). It appears that heat tolerance may not be compromised by age in healthy and physically active older individuals. A decrease in heat tolerance with age reported in some of the earlier studies seems to be due to deconditioning and/or a lack of heat acclimatization in older subjects.

As more and more people become and remain physically active throughout middle age and advanced years, it may be expected that older individuals tolerate exercise in the heat just as well as younger adults. However, caution should still be made in that with advancing age the elderly will lose their sweat glands progressively over time. In addition, Kenney and Chiu (2001) have found that during exercise in a warm environment, older adults exhibit reduced thirst sensation and thus decreased voluntary fluid intake. Therefore, older individuals need to be especially diligent in following recommended hydration strategies before, during, and after exercise. Voluntary fluid consumption in the elderly may be enhanced by using electrolyte-carbohydrate solution. Baker *et al.* (2005) found that older adults drank enough to maintain fluid balance when palatable fluid, such as carbohydrate-electrolyte solution, was readily available.

When compared to adolescents and adults, children may produce more metabolic heat during exercise relative to their body size. This is caused by the fact that children are not as metabolically efficient in performing physical activity as compared to adults. Children don't sweat as much, although they have a greater number of heat-activated sweat glands per unit skin area than do adults (Falk *et al.* 1992). In addition, children have a reduced capacity to convey heat from the core to the skin and take longer to acclimatize to heat than do adolescents and adults. These age differences suggest that, when exposed to environmental heat stress, children should exercise at reduced intensity and allow more time to adapt to the environment.

Level of body fat

Excess body fat negatively affects exercise performance in hot environments. Extra fat directly adds to the metabolic cost of weight-bearing activity. Extra fat also increases insulation of the body shell and thus retards heat dissipation from the body to the surroundings. Therefore, obese individuals not only generate more heat during exercise, but also have high amounts of body fat to deter heat loss. In the case of American football, the additional demands of equipment weight (i.e., football gear), intense competition, and a hot, humid environment compound these effects. Thus, overweight athletes, especially linemen who generally have more body fat, can experience considerable difficulty in temperature regulation and exercise performance. In the Marine Corps study cited previously, another major predictor of exertional heat illness was a high body mass index, which correlates with percent body fat in most cases.

Heat acclimatization

Another more important factor in determining an individual's response to exercise in the heat is degree of **heat acclimatization**. Heat acclimatization refers to the process in which regular exercise in a hot environment results in a series of physiological adjustments designed to minimize disturbances in homeostasis due to heat stress. The primary adaptations that occur during heat acclimatization are an increased plasma volume, earlier onset of sweating, higher sweat rate, reduced sodium loss in sweat, reduced skin blood flow, and reduced use of muscle glycogen. These adaptations take place relatively rapidly, with almost complete acclimatization being achieved by 7 to 14 days after the first exposure to the heat. Although partial heat acclimatization may occur by training in a cool environment, athletes must exercise in a hot environment to obtain maximal heat acclimatization (Armstrong and Maresh 1991).

As stated previously, heat acclimatization results in earlier onset of sweating. This means that sweating begins rapidly after the commencement of exercise, which translates into lower heat storage at the beginning of exercise and a lower core temperature. In addition, heat acclimatization also increases sweat capacity almost threefold above the rate achieved prior to heat acclimatization (Yanagimoto *et al.* 2002). Therefore, much more evaporative cooling is possible. As a result, skin temperatures are lower. This then increases the temperature gradient from deep in the body to the skin and the environment. Because heat loss is facilitated via sweat, less blood must flow to the skin for body heat transfer, so more blood is available for the active muscles. In addition, the sweat produced is more diluted following training in heat, so the body's mineral stores are conserved.

Heat acclimatization may result in a 10 percent gain in plasma volume (Gisolfi and Cohen 1979). The increase in plasma volume is due to an increase in plasma proteins and sodium content, which function to draw more fluids into the blood via osmosis. This

increased plasma volume maintains central blood volume, venous return, stroke volume, and sweating capacity, and allows the body to store more heat with a smaller rise in body temperature. The increased plasma volume coupled with reduced blood flow to the skin causes the heart rate to increase less in response to a submaximal exercise. This lower increase in heart rate contributes to an increase in stroke volume.

Summary

- The body's thermostat is located in the hypothalamus. An increase in core temperature results in the hypothalamus initiating a series of physiological actions aimed at increasing heat loss. These actions include sweating and skin vasodilation.
- The body produces heat due to normal metabolic processes. Metabolic heat production is small at rest or during sleep. However, during intense exercise, heat production is large. The heat production may be classified as voluntary and involuntary. Voluntary heat production is brought about by exercise, whereas involuntary heat production results from shivering or the secretion of hormones, such as thyroxine and catecholamines.
- The heat produced in the body must have access to the outside world. The heat from deep in the body (core) is moved by the blood to the skin (the shell). Once heat nears the skin, it can be transferred to the environment by any of the four mechanisms: conduction, convection, radiation, and evaporation. Radiation is the primary means for dissipating the body's excess heat at rest, whereas evaporation functions as a major defense against overheating during exercise.
- Evaporation of sweat from the skin is dependent on three factors: (1) the temperature and relative humidity; (2) the convective current around the body, and (3) the amount of skin surface. Warm, humid environments dramatically decrease the effectiveness of evaporative heat loss. This increases one's vulnerability to a dangerous state of dehydration.
- The circulatory system serves as the "driving force" to maintain thermal balance. In hot weather, heart rate and blood flow from the heart increase while superficial arterial and venous blood-vessels dilate to divert warm blood to the body's shell. This circulatory adjustment may hamper blood and oxygen supply to the working muscle.
- Maintenance of fluid balance results from both neural and hormonal regulation. When the body becomes dehydrated, the thirst center in the hypothalamus triggers the drive to drink, and the kidneys retain more fluids via the action of anti-diuretic hormone and aldosterone. Fluid replacement should be carefully carried out. While excessive loss of water may cause dehydration, consuming too much water without electrolytes may lead to hyponatremia.
- Fluid loss in excess of 2 percent of body mass impedes heat dissipation, compromises cardiovascular function, and diminishes exercise capacity in a hot environment. The reasons dehydration has an adverse effect on exercise performance may be attributed mainly to factors that are cardiovascular and metabolic in origin, and these factors include reduced cardiac output, increased heart rate, accelerated glycogen use, increased lactate production, altered electrolyte balance, and impaired cognitive function.
- Rehydration based on thirst sensation is not a reliable approach. Athletes should become accustomed to consuming fluids at regular intervals with and without thirst during training sessions. The amount to be rehydrated should at least match sweat loss incurred during exercise. However, athletes are encouraged to ingest more than their sweat loss in order to account for urine loss associated with beverage consumption.

- Adding carbohydrate to a replacement fluid has the potential to hamper gastric emptying and thus fluid absorption. Thus, caution should be exercised in choosing a sports drink. In cool environments, where substrate provision to maintain endurance performance is more important, a concentrated solution containing large amounts of glucose is recommended. When dehydration or hyperthermia is the major threat to performance, fluid replacement is the primary consideration. In very prolonged exercise in the heat with heavy sweat loss, such as ultramarathons, carbohydrate and electrolyte replacement is essential to prevent heat injury.
- Heat cramps, heat exhaustion, and heat-stroke are the major forms of heat illness. Heat-stroke represents the most serious and complex of these heat-related disorders.
- Repeated heat stress initiates thermoregulatory adjustments that improve exercise capacity. The primary adaptations that occur during heat acclimatization are an increased plasma volume, earlier onset of sweating, higher sweat rate, reduced sodium lost in sweat, reduced skin blood flow, and reduced use of muscle glycogen.
- When controlling for fitness and acclimatization levels, women and men show equal thermoregulatory efficiency during exercise. Women produce less sweat than men do and rely more on circulatory cooling. This gender difference may impose a greater circulatory strain upon women than upon men. However, less sweat production to maintain thermal balance may protect women from dehydration during exercise in the heat.
- Aging may impair thermoregulatory function. However, this impairment appears to be fitness related. Older and young men with a similar level of training show little difference in thermoregulation during exercise as well as the ability to acclimatize to heat stress.

Case study: fighting against heat cramps

Devon is a talented 17-year-old tennis player. He trained hard, competed regularly with the best, and attained a respectable national ranking. He was accustomed to doing well in the early rounds of most tournaments. Unfortunately, after winning several matches, particularly in events held in hot weather, Devon often faced an unyielding opponent that many of his counterparts seem to avoid: heat cramps. These debilitating muscle cramps, which primarily affected Devon's legs, occurred despite his efforts to hydrate and eat well between matches. Devon has talked to a number of trainers and physicians and tried a variety of "remedies," but none of them seems to work. It wasn't until recently that Devon's physician noticed that Devon's family regularly consumed a diet fairly low in salt due to the fact that his father had high blood pressure. Subsequent laboratory testing also revealed that Devon had high rates of fluid and sodium loss via sweating during competitions. Because of these findings, Devon was urged by his physician to increase his daily salt intake and to pay more attention to appropriate fluid intake in order to prevent heat cramps.

Questions

- How would you define the condition of heat cramps? What causes heat cramps?
- How does heat cramp differ from other heat illness, such as heat exhaustion and heat-stroke?
- What would you recommend Devon do to maintain an adequate sodium concentration, especially during tournaments?

Review questions

1 Discuss the role of the hypothalamus in temperature regulation.
2 List and define the four heat-dissipating mechanisms. Which of these heat loss avenues plays the most important part during exercise in a hot/dry environment?
3 How does an increase in exercise intensity affect the total heat production, evaporative heat loss, convective heat loss, and radiant heat loss?
4 How are (1) sweat loss, (2) sweat rate, and (3) dehydration determined?
5 Explain the role of circulation in heat dissipation. Why does heart rate often experience a greater increase during exercise in heat as compared to thermo-neutral conditions?
6 Your friend is going to run a marathon. The projected weather forecast is sunny, warm, and humid. What advice would you offer regarding consumption of fluid, including carbohydrate and electrolytes, before and during the race?
7 Explain the role of (1) anti-diuretic hormone, and (2) aldosterone in regulating fluid balance in the body.
8 What are the physiological mechanisms responsible for why dehydration reduces sports performance?
9 How do men and women differ in responding to heat stress?
10 Define heat cramps, heat exhaustion, and heat-stroke. What are the major symptoms associated with each of these heat-related injuries?
11 Define the term heat acclimatization. List those adaptive changes that will occur because of heat acclimatization and discuss how they may help restore exercise performance.

Suggested reading

1 American College of Sports Medicine, Sawka MN, Burke LM, Eichner ER, Maughan RJ, Montain SJ, Stachenfeld NS (2007) American College of Sports Medicine Position Stand. Exercise and fluid replacement. *Medicine and Science in Sports and Exercise*, 39: 377–390.
This position stand provides the most current and evidence-based guidance on fluid replacement to sustain appropriate hydration of individuals performing physical activity. It represents an official view of the American College of Sports Medicine toward thermoregulation and fluid replacement.
2 Maughan RJ, Shirreffs SM (2010) Development of hydration strategies to optimize performance for athletes in high-intensity sports and in sports with repeated intense efforts. *Scandinavian Journal of Medical Science and Sports*, 20 (Suppl 2): 59–69.
Athletes should assess their hydration status and develop a personalized hydration strategy that takes account of exercise, environment, and individual needs. This review provides a comprehensive yet practical guide that may be used by competitive athletes to minimize the strain imposed by heat and dehydration.
3 Wendt D, van Loon LJ, Lichtenbelt WD (2007) Thermoregulation during exercise in the heat: strategies for maintaining health and performance. *Sports Medicine*, 37: 669–682.
During exercise, several powerful physiological mechanisms of heat loss are activated to prevent an excessive rise in body core temperature. However, a hot and humid environment can significantly add to the challenge that physical exercise imposes upon the body. This article provides a thorough review on thermoregulation and hydration strategies for maintaining health and performance.

Glossary

Aldosterone a hormone from the adrenal cortex that instructs the kidneys to retain more sodium.

Anti-diuretic hormone a hormone from the posterior pituitary gland that instructs the kidneys to conserve water and electrolytes.

Conduction a process of heat loss via the transfer of heat from the body into the molecules of a cooler object in contact with the body's surface.

Convection a process of heat loss through movement of air or water molecules in contact with the body.

Dehydration a condition where there is an excessive loss of body fluid.

Evaporation a process of heat loss when water is converted from its liquid form into its vapor form.

Gastric emptying the process by which food leaves the stomach and enters the duodenum.

Glucose electrolyte solutions the first commercial fluid replacement preparations designed for athletes to replace fluid and carbohydrate lost during training and competition.

Glucose polymer solutions fluid replacement preparations designed to provide carbohydrate while decreasing the osmotic concentration of the solution, thus helping with fluid absorption.

Heat acclimatization the process in which regular exercise in a hot environment results in a series of physiological adjustments designed to minimize disturbances in homeostasis due to heat stress.

Hyperhydration an attempt to begin an exercise bout with a slight surplus of body water.

Hyponatremia also regarded as water intoxication resulting from excessive water ingestion.

Involuntary heat production the heat production that results from shivering or the secretion of hormones such as thyroxine and catecholamines.

Maltodextrin a glucose polymer that exerts lesser osmotic effects compared with glucose and is thus used in a variety of sports drinks as the source of carbohydrate.

Non-shivering thermogenesis an increase in heat production due to the combined influences of thyroxine and catecholamines.

Osmolality a measure of solute concentration of a solution.

Radiation a process of heat loss in the form of infrared rays.

Relative humidity the percentage of water in ambient air at a particular temperature compared with the total quantity of moisture that air could carry.

Rhabdomyolysis a condition in which damaged tissue leaks its contents into the blood, eventually leading to kidney damage and possible death.

Stroke volume the amount of blood ejected by the heart per beat.

Thirst the desire to drink and the sensation triggered by a lack of fluids in the body.

Voluntary heat production the heat production brought about by exercise or physical activity.

Appendix A

Metric units, English–metric conversions, and cooking measurement equivalents

Dry measure

1 pint = 0.55 liter
1 quart = 1.10 liters
1 peck = 8.81 liters
1 bushel = 35.24 liters

Liquid measure

1 pint = 0.47 liter
1 quart = 0.946 liter
1 gallon = 3.79 liters

Weight

1 ounce = 28.35 grams
1 pound = 0.45 kilograms
1 short ton = 0.91 metric ton
1 long ton = 1.02 metric tons
1000 milligrams = 1 gram
1000 grams = 1 kilogram
1000 kilograms = 1 metric ton

Length

1 inch = 2.54 centimeters
1 yard = 0.91 meter
1 mile = 1.61 kilometers
1 kilometer = 0.6 mile
10 millimeters = 1 centimeter
10 centimeters = 1 decimeter
10 decimeters = 1 meter
1000 meters = 1 kilometer

Area/square measure

1 square inch = 6.4516 square centimeters
1 square foot = 9.29034 square decimeters
1 square yard = 0.836131 square meter
1 acre = 4046.85642 square meters
1 square mile = 2.59 square kilometers
100 square millimeters = 1 square centimeter
100 square centimeters = 1 square decimeter
100 square decimeters = 1 square meter

Volume/cubic measure

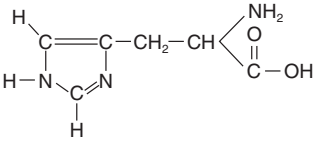
1 cubic inch = 16.34 cubic centimeters
1 cubic foot = 0.28 cubic meters
1 cubic yard = 0.76 cubic meters
10 milliliters = 1 centiliter
10 centiliters = 1 deciliter
10 deciliters = 1 liter

Cooking measurement equivalents

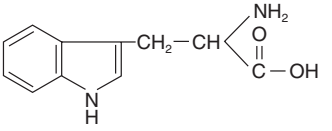
16 tablespoons = 1 cup
4 tablespoons = 1/4 cup
1 tablespoons = 1/16 cup
8 fluid ounces = 1 cup
1 quart = 2 pints
1 gallon = 4 quarts
8 tablespoons = 1/2 cup
2 tablespoons = 1/8 cup
1 tablespoons = 3 teaspoons
1 pint = 2 cups
4 cups = 1 quart
16 ounces = 1 pound

Appendix B

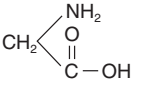
Chemical structure of amino acids



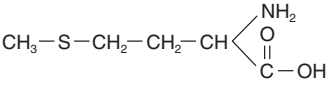
(1) Histidine (His)
(essential)



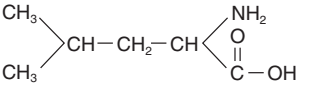
(2) Tryptophan (Trp)
(essential)



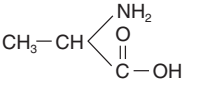
(3) Glycine (Gly)



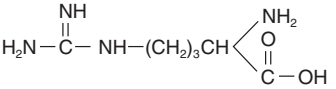
(4) Methionine (Met)
(essential)



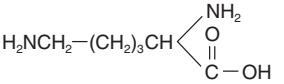
(5) Leucine (Leu)
(essential)



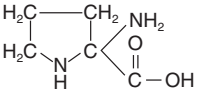
(6) Alanine (Ala)



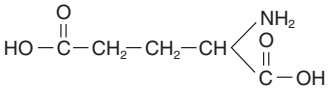
(7) Arginine (Arg)
(essential in infancy)



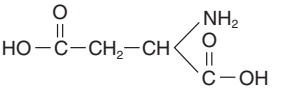
(8) Lysine (Lys)
(essential)



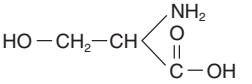
(9) Proline (Pro)



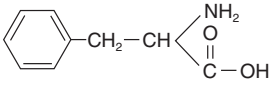
(10) Glutamic acid (Glu)



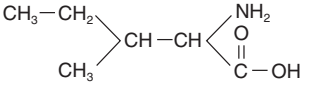
(11) Aspartic acid (Asp)



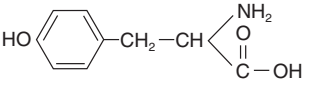
(12) Serine (Ser)



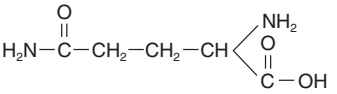
(13) Phenylalanine (Phe)
(essential)



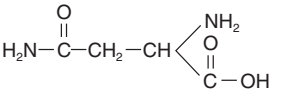
(14) Isoleucine (Ile)
(essential)



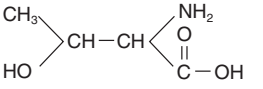
(15) Tyrosine (Tyr)



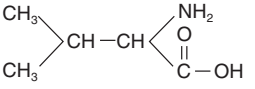
(16) Glutamine (Gln)



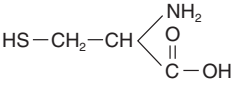
(17) Asparagine (Asn)



(18) Threonine (Thr)
(essential)



(19) Valine (Val)
(essential)



(20) Cysteine (Cys)

Appendix C

Dietary reference intakes for energy, macronutrients, and micronutrients

The dietary reference intakes (DRIs) include two sets of values that serve as goals for nutrient intake: recommended dietary allowances (RDAs) and adequate intake (AI). The RDA reflects the average daily amount of a nutrient considered adequate to meet the needs of most healthy people. If there is insufficient evidence to determine an RDA, an AI is set.

Table C.1 Dietary reference intakes (DRIs): recommended dietary allowances and adequate intakes, total water and macronutrients. Food and Nutrition Board, Institute of Medicine, National Academies

Life stage group	*Total water*[a] *(L/d)*	*Carbohydrate (g/d)*	*Total fiber (g/d)*	*Fat (g/d)*	*Linoleic acid (g/d)*	*α-Linolenic acid (g/d)*	*Protein*[b] *(g/d)*
Infants							
0 to 6 months	0.7*	60*	ND	31*	4.4*	0.5*	9.1*
6 to 12 months	0.8*	95*	ND	30*	4.6*	0.5*	**11.0**
Children							
1–3 years	1.3*	**130**	19*	ND[c]	7*	0.7*	**13**
4–8 years	1.7*	**130**	25*	ND	10*	0.9*	**19**
Males							
9–13 years	2.4*	**130**	31*	ND	12*	1.2*	**34**
14–18 years	3.3*	**130**	38*	ND	16*	1.6*	**52**
19–30 years	3.7*	**130**	38*	ND	17*	1.6*	**56**
31–50 years	3.7*	**130**	38*	ND	17*	1.6*	**56**
51–70 years	3.7*	**130**	30*	ND	14*	1.6*	**56**
>70 years	3.7*	**130**	30*	ND	14*	1.6*	**56**

Females							
9–13 years	2.1*	**130**	26*	ND	10*	1.0*	**34**
14–18 years	2.3*	**130**	26*	ND	11*	1.1*	**46**
19–30 years	2.7*	**130**	25*	ND	12*	1.1*	**46**
31–50 years	2.7*	**130**	25*	ND	12*	1.1*	**46**
51–70 years	2.7*	**130**	21*	ND	11*	1.1*	**46**
>70 years	2.7*	**130**	21*	ND	11*	1.1*	**46**
Pregnancy							
14–18 years	3.0*	**175**	28*	ND	13*	1.4*	**71**
19–30 years	3.0*	**175**	28*	ND	13*	1.4*	**71**
31–50 years	3.0*	**175**	28*	ND	13*	1.4*	**71**
Lactation							
14–18 years	3.8*	**210**	29*	ND	13*	1.3*	**71**
19–30 years	3.8*	**210**	29*	ND	13*	1.3*	**71**
31–50 years	3.8*	**210**	29*	ND	13*	1.3*	**71**

Source: *Dietary Reference Intakes for Energy, Carbohydrates, Fiber, Fat, Fatty Acids, Cholesterol, Protein, and Amino Acids* (2002/2005) and *Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate* (2005). The report may be accessed via www.nap.edu.

Notes

This table (taken from the DRI reports: see www.nap.edu) presents recommended dietary allowances (RDAs) in **bold type** and adequate intakes (AI) in ordinary type followed by an asterisk (*). A RDA is the average daily dietary intake level, sufficient to meet the nutrient requirements of nearly all (97–98%) healthy individuals in a group. It is calculated from an estimated average requirement (EAR). If sufficient scientific evidence is not available to establish an EAR, and thus calculate a RDA, an AI is usually developed. For healthy breastfed infants, an AI is the mean intake. The AI for other life stage and gender groups is believed to cover the needs of all healthy individuals in the groups, but lack of data or uncertainty in the data prevent one from being able to specify with confidence the percentage of individuals covered by this intake.

a *Total* water includes all water contained in food, beverages, and drinking water.

b Based on g protein per kg of body weight for the reference body weight, e.g., for adults 0.8 g/kg body weight for the reference body weight.

c Not determined.

Table C.2 Dietary reference intakes (DRIs): recommended dietary allowances and adequate intakes, vitamins. Food and Nutrition Board, Institute of Medicine, National Academies

Life stage group	*Vitamin A (μg/d)*[a]	*Vitamin C (mg/d)*	*Vitamin D (μg/d)*[b,c]	*Vitamin E (mg/d)*[d]	*Vitamin K (μg/d)*	*Thiamin (mg/d)*	*Riboflavin (mg/d)*	*Niacin (mg/d)*[e]	*Vitamin B_6 (mg/d)*	*Folate (μg/d)*[f]	*Vitamin B_{12} (μg/d)*	*Pantothenic acid (mg/d)*	*Biotin (μg/d)*	*Choline (mg/d)*[g]
Infants														
0 to 6 months	400*	40*	10	4*	2.0*	0.2*	0.3*	2*	0.1*	65*	0.4*	1.7*	5*	125*
6 to 12 months	500*	50*	10	4*	2.5*	0.3*	0.4*	4*	0.3*	80*	0.5*	1.8*	6*	150*
Children														
1–3 years	**300**	**15**	**15**	6	30*	**0.5**	**0.5**	6	**0.5**	**150**	**0.9**	2*	8*	200*
4–8 years	400	**25**	**15**	7	55*	**0.6**	**0.6**	8	**0.6**	**200**	**1.2**	3*	12*	250*
Males														
9–13 years	**600**	**45**	**15**	11	60*	**0.9**	**0.9**	12	**1.0**	**300**	**1.8**	4*	20*	375*
14–18 years	**900**	**75**	**15**	15	75*	**1.2**	**1.3**	16	**1.3**	**400**	**2.4**	5*	25*	550*
19–30 years	**900**	**90**	**15**	15	120*	**1.2**	**1.3**	16	**1.3**	**400**	**2.4**	5*	30*	550*
31–50 years	**900**	**90**	**15**	15	120*	**1.2**	**1.3**	16	**1.3**	**400**	**2.4**	5*	30*	550*
51–70 years	**900**	**90**	**15**	15	120*	**1.2**	**1.3**	16	**1.7**	**400**	**2.4**[h]	5*	30*	550*
>70 years	**900**	**90**	**20**	15	120*	**1.2**	**1.3**	16	**1.3**	**400**	**2.4**[h]	5*	30*	550*
Females														
9–13 years	**600**	**45**	**15**	11	60*	**0.9**	**0.9**	12	**1.0**	**300**	**1.8**	4*	20*	375*
14–18 years	**700**	**65**	**15**	15	75*	**1.0**	**1.0**	14	**1.2**	**400**[i]	**2.4**	5*	25*	400*
19–30 years	**700**	**75**	**15**	15	90*	**1.1**	**1.1**	14	**1.3**	**400**[i]	**2.4**	5*	30*	425*
31–50 years	**700**	**75**	**15**	15	90*	**1.1**	**1.1**	14	**1.3**	**400**[i]	**2.4**	5*	30*	425*
51–70 years	**700**	**75**	**15**	15	90*	**1.1**	**1.1**	14	**1.5**	**400**	**2.4**[h]	5*	30*	425*
>70 years	**700**	**75**	**20**	15	90*	**1.1**	**1.1**	14	**1.3**	**400**	**2.4**[h]	5*	30*	425*
Pregnancy														
14–18 years	**750**	**80**	**15**	15	75*	**1.4**	**1.4**	18	**1.9**	**600**[j]	**2.6**	6*	30*	450*
19–30 years	**770**	**85**	**15**	15	90*	**1.4**	**1.4**	18	**1.9**	**600**[j]	**2.6**	6*	30*	450*
31–50 years	**770**	**85**	**15**	15	90*	**1.4**	**1.4**	18	**1.9**	**600**[j]	**2.6**	6*	30*	450*
Lactation														
14–18 years	**1200**	**115**	**15**	19	75*	**1.4**	**1.6**	17	**2.0**	**500**	**2.8**	7*	35*	550*
19–30 years	**1300**	**120**	**15**	19	90*	**1.4**	**1.6**	17	**2.0**	**500**	**2.8**	7*	35*	550*
31–50 years	**1300**	**120**	**15**	19	90*	**1.4**	**1.6**	17	**2.0**	**500**	**2.8**	7*	35*	550*

Sources: *Dietary Reference Intakes for Calcium, Phosphorous, Magnesium, Vitamin D, and Fluoride* (1997); *Dietary Reference Intakes for Thiamin, Riboflavin, Niacin, Vitamin B_6, Folate, Vitamin B_{12}, Pantothenic Acid, Biotin, and Choline* (1998); *Dietary Reference Intakes for Vitamin C, Vitamin E, Selenium, and Carotenoids* (2000); *Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Magnesium, Molybdenum, Nickel, Silicon, Vanadium, and Zinc* (2001); *Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate* (2005); and *Dietary Reference Intakes for Calcium and Vitamin D* (2011). These reports may be accessed via www.nap.edu.

Notes

This table (taken from the DRI reports, see www.nap.edu) presents recommended dietary allowances (RDAs) in **bold type** and adequate intakes (AIs) in ordinary type followed by an asterisk (*). A RDA is the average daily dietary intake level, sufficient to meet the nutrient requirements of nearly all (97–98%) healthy individuals in a group. It is calculated from an estimated average requirement (EAR). If sufficient scientific evidence is not available to establish an EAR, and thus calculate a RDA, an AI is usually developed. For healthy breastfed infants, an AI is the mean intake. The AI for other life stage and gender groups is believed to cover the needs of all healthy individuals in the groups, but lack of data or uncertainty in the data prevent one from being able to specify with confidence the percentage of individuals covered by this intake.

a As retinol activity equivalents (RAEs), 1 RAE = 1 μg retinol, 12 μg β-carotene, 24 μg α-carotene, or 24 μg β-cryptoxanthin. The RAE for dietary provitamin A carotenoids is twofold greater than retinol equivalents (RE), whereas the RAE for preformed vitamin A is the same as RE.

b As cholecalciferol. 1 μg cholecalciferol = 40 IU vitamin D.

c Under the assumption of minimal sunlight.

d As α-tocophenol. α-Tocophenol includes *RRR*-α-tocophenol, the only form of α-tocophenol that occurs naturally in foods, and the 2*R*-stereoisomeric forms of α-tocophenol (*RRR*-, *RSR*-, *RRS*-, and *RSS*-α-tocophenol) that occurs in fortified foods and supplements. It does not include the 2*S*-stereoisomeric forms of α-tocophenol (*SRR*-, *SSR*-, *SRS*-, and *SSS*-α-tocophenol), also found in fortified foods and supplements.

e As niacin equivalents (NE). 1 mg of niacin = 60 mg of tryptophan; 0–6 months = performed niacin (not NE).

f As dietary folate equivalents (DFE). 1 DFE = 1 μg food folate - 0.6 μg of folic acid from fortified food or as a supplement consumed with food = 0.5 μg of a supplement taken on an empty stomach.

g Although AIs have been set for choline, there are few data to assess whether a dietary supply of choline is needed at all stages of the life cycle, and it may be that the choline requirements can be met by endogenous synthesis at some of these stages.

h Because 10 to 30 percent of older people may malabsorb food-bound B_1, it is advisable for those older than 50 years to meet their RDA mainly by consuming foods fortified with B_{12} or a supplement containing B_1.

i In view of evidence linking folate intake with neural tube defects in the fetus, it is recommended that all women capable of becoming pregnant consume 400 μg from supplements or fortified foods in addition to intake of food folate from a varied diet.

j It is assumed that women will continue consuming 400 μg from supplements or fortified food until their pregnancy is confirmed and they enter prenatal care, which ordinarily occurs after the end of the periconceptional period – the critical time for formation of the neural tube.

Table C.3 Dietary reference intakes (DRIs): recommended dietary allowances and adequate intakes, elements. Food and Nutrition Board, Institute of Medicine, National Academies

Life stage group	*Calcium (mg/d)*	*Chromium (µg/d)*	*Copper (µg/d)*	*Fluoride (mg/d)*	*Iodine (µg/d)*	*Iron (mg/d)*	*Magnesium (mg/d)*	*Manganese (mg/d)*	*Molybdenum (µg/d)*	*Phosporus (mg/d)*	*Selenium (µg/d)*	*Zinc (mg/d)*	*Potassium (g/d)*	*Sodium (g/d)*	*Chloride (g/d)*
Infants															
0 to 6 months	200*	0.2*	200*	0.01*	110*	0.27*	30*	0.003*	2*	100*	15*	2*	0.4*	0.12*	0.18*
6 to 12 months	200*	5.5*	220*	0.5*	130*	11	75*	0.6*	3*	275*	20*	3	0.7*	0.37*	0.5718*
Children															
1–3 years	**700**	11*	**340**	0.7*	**90**	**7**	**80**	1.2*	**17**	**460**	**20**	**3**	3.0*	1.0*	1.5*
4–8 years	**1000**	15*	**440**	1*	**90**	**10**	**130**	1.5*	**22**	**500**	**30**	**5**	3.8*	1.2*	1.9*
Males															
9–13 years	**1300**	25*	**700**	2*	**120**	**8**	**240**	1.9*	**34**	**1250**	**40**	**8**	4.5*	1.5*	2.3*
14–18 years	**1300**	35*	**890**	3*	**150**	**11**	**410**	2.2*	**43**	**1250**	**55**	**11**	4.7*	1.5*	2.3*
19–30 years	**1000**	35*	**900**	4*	**150**	**8**	**400**	2.3*	**45**	**700**	**55**	**11**	4.7*	1.5*	2.3*
31–50 years	**1000**	35*	**900**	4*	**150**	**8**	**400**	2.3*	**45**	**700**	**55**	**11**	4.7*	1.5*	2.3*
51–70 years	**1000**	30*	**900**	4*	**150**	**8**	**400**	2.3*	**45**	**700**	**55**	**11**	4.7*	1.3*	2.0*
>70 years	**1200**	30*	**900**	4*	**150**	**8**	**400**	2.3*	**45**	**700**	**55**	**11**	4.7*	1.2*	1.8*
Females															
9–13 years	**1300**	21*	**700**	2*	**120**	**8**	**240**	1.6*	**34**	**1250**	**40**	**8**	4.5*	1.5*	2.3*
14–18 years	**1300**	24*	**890**	3*	**150**	**15**	**360**	1.6*	**43**	**1250**	**55**	**9**	4.7*	1.5*	2.3*
19–30 years	**1000**	25*	**900**	3*	**150**	**18**	**310**	1.8*	**45**	**700**	**55**	**8**	4.7*	1.5*	2.3*
31–50 years	**1000**	25*	**900**	3*	**150**	**18**	**320**	1.8*	**45**	**700**	**55**	**8**	4.7*	1.5*	2.3*
51–70 years	**1200**	20*	**900**	3*	**150**	**8**	**320**	1.8*	**45**	**700**	**55**	**8**	4.7*	1.3*	2.0*
>70 years	**1200**	20*	**900**	3*	**150**	**8**	**320**	1.8*	**45**	**700**	**55**	**8**	4.7*	1.2*	1.8*

Pregnancy															
14–18 years	**1300**	29*	**1000**	3*	**220**	**27**	**400**	2.0*	**50**	**1250**	**60**	**12**	4.7*	1.5*	2.3*
19–30 years	**1000**	30*	**1000**	3*	**220**	**27**	**350**	2.0*	**50**	**700**	**60**	**11**	4.7*	1.5*	2.3*
31–50 years	**1000**	30*	**1000**	3*	**220**	**27**	**360**	2.0*	**50**	**700**	**60**	**11**	4.7*	1.5*	2.3*
Lactation															
14–18 years	**1300**	44*	**1300**	3*	**290**	**10**	**360**	2.6*	**50**	**1250**	**70**	**13**	5.1*	1.5*	2.3*
19–30 years	**1000**	45*	**1300**	3*	**290**	**9**	**310**	2.6*	**50**	**700**	**70**	**12**	5.1*	1.5*	2.3*
31–50 years	**1000**	45*	**1300**	3*	**290**	**9**	**320**	2.6*	**50**	**700**	**70**	**12**	5.1*	1.5*	2.3*

Sources: *Dietary Reference Intakes for Calcium, Phosphorous, Magnesium, Vitamin D, and Fluoride* (1997); *Dietary Reference Intakes for Thiamin, Riboflavin, Niacin, Vitamin B_6, Folate, Vitamin B_{12}, Pantothenic Acid, Biotin, and Choline* (1998); *Dietary Reference Intakes for Vitamin C, Vitamin E, Selenium, and Carotenoids* (2000); *Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Magnesium, Molybdenum, Nickel, Silicon, Vanadium, and Zinc* (2001); *Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate* (2005); and *Dietary Reference Intakes for Calcium and Vitamin D* (2011). These reports may be accessed via www.nap.edu.

Notes

This table (taken from the DRI reports, see www.nap.edu) presents recommended dietary allowances (RDAs) in **bold type** and adequate intakes (AIs) in ordinary type followed by an asterisk (*). A RDA is the average daily dietary intake level, sufficient to meet the nutrient requirements of nearly all (97–98 %) healthy individuals in a group. It is calculated from an estimated average requirement (EAR). If sufficient scientific evidence is not available to establish an EAR, and thus calculate a RDA, an AI is usually developed. For healthy breastfed infants, an AI is the mean intake. The AI for other life stage and gender groups is believed to cover the needs of all healthy individuals in the groups, but lack of data or uncertainty in the data prevent one from being able to specify with confidence the percentage of individuals covered by this intake.

Appendix D

Estimated energy requirement calculations and physical activity values

Table D.1 Estimated energy requirement calculations

Age group	*Equations for estimated energy requirement (EER; kcal/d)*[a]
0–3 months	[89 × weight (kg) – 100] + 75
4–6 months	[89 × weight (kg) – 100] + 56
7–12 months	[89 × weight (kg) – 100] + 22
13–36 months	[89 × weight (kg) – 100] + 20
3–8 years (male)	88.5 – [61.9 × age (y)] + PA × [26.7 × weight (kg) + 903 × height (m)] + 20
3–8 years (female)	135.3 – [30.8 × age (y)] + PA × [10.0 × weight (kg) + 934 × height (m)] + 20
9–18 years (male)	88.5 – [61.9 × age (y)] + PA × [26.7 × weight (kg) + 903 × height (m)] + 25
9–18 years (female)	135.3 – [30.8 × age (y)] + PA × [10.0 × weight (kg) + 934 × height (m)] + 25
19+ years (male)	662 – [9.53 × age (y)] + PA × [15.91 × weight (kg) + 539.6 × height (m)]
19+ years (female)	354 – [6.91 × age (y)] + PA × [9.36 × weight (kg) + 726 × height (m)]
Pregnancy	
14–18 years	
First trimester	Adolescent EER + 0
Second trimester	Adolescent EER + 340
Third trimester	Adolescent EER + 452
19–50 years	
First trimester	Adult EER + 0
Second trimester	Adult EER + 340
Third trimester	Adult EER + 452
Lactation	
4–18 years	
First trimester	Adolescent EER + 330
Second trimester	Adolescent EER + 400
19–50 years	
First trimester	Adult EER + 330
Second trimester	Adult EER + 400
Overweight or obese[b]	
3–18 years (male)	114 – [50.9 × age (y)] + PA × [19.5 × weight (kg) + 1161.4 × height (m)]
3–18 years (female)	389 – [41.2 × age (y)] + PA × [15.0 × weight (kg) + 701.6 × height (m)]
19+ years (male)	1086 – [10.1 × age (y)] + PA × [13.7 × weight (kg) + 416 × height (m)]
19+ years (female)	448 – [7.95 × age (y)] + PA × [11.4 × weight (kg) + 619 × height (m)]

Notes

a "PA" stands for the "physical activity" value appropriate for the age and physiological state. These may be found in the next table.

b Body mass index (BMI ≥25 kg/m^2; values represent estimated total energy expenditure (TEE; kcal/d) for weight maintenance; weight loss may be achieved by a reduction in energy intake and/or an increase in energy expenditure.

Table D.2 Physical activity (PA) values

Age group (sex)	*Physical activity level*[a]	*Physical activity (PA) value*
3–8 years (male)	Sedentary	1.00
	Low active	1.13
	Active	1.26
	Very active	1.42
3–8 years (female)	Sedentary	1.00
	Low active	1.16
	Active	1.31
	Very active	1.56
3–18 years (overweight male)[b]	Sedentary	1.00
	Low active	1.12
	Active	1.24
	Very active	1.45
3–18 years (overweight female)[b]	Sedentary	1.00
	Low active	1.18
	Active	1.35
	Very active	1.60
9–18 years (male)	Sedentary	1.00
	Low active	1.13
	Active	1.26
	Very active	1.42
9–18 years (female)	Sedentary	1.00
	Low active	1.16
	Active	1.31
	Very active	1.56
19+ years (male)	Sedentary	1.00
	Low active	1.11
	Active	1.25
	Very active	1.48
19+ years (female)	Sedentary	1.00
	Low active	1.12
	Active	1.27
	Very active	1.45
19+ years (overweight male)[b]	Sedentary	1.00
	Low active	1.12
	Active	1.29
	Very active	1.59
19+ years (overweight female)[b]	Sedentary	1.00
	Low active	1.16
	Active	1.27
	Very active	1.44

Source: Institute of Medicine (2005).

Notes

a *Sedentary* activity level is characterized by no physical activity aside from that needed for independent living. *Low active* level is characterized by walking 1.5–3 miles/day at 2–4 mph (or equivalent) in addition to the light activity associated with typical day-to-day life. People who are *active* walk 3–10 miles/day at 2–4 mph (or equivalent) in addition to the light activity associated with typical day-to-day life. *Very active* individuals walk 10 or more miles/day at 2–4 mph (or equivalent) in addition to the light activity associated with typical day-to-day life.

b Body mass index (BMI) = 25 kg/m^2.

Appendix E

Daily values used in food labels with a comparison to RDAs

Table E.1 Daily values used in food labels with a comparison to RDAs

Dietary constituent	*Unit of measure*	*Daily values for people over 4 years of age**	*RDA for males*	*RDA for females*
Total fat	g	<65	–	–
Saturated fatty acids	g	<20	–	–
Protein	g	50	56	46
Cholesterol	mg	<300	–	–
Carbohydrate	g	~300	130	130
Fiber	g	25	38	25
Vitamin A	μg	1000	900	700
Vitamin D	IU	400	200	200
Vitamin E	IU	30	22–33	22–33
Vitamin K	μg	80	120	90
Vitamin C	mg	60	90	75
Folate	μg	400	400	400
Thiamin	mg	1.5	1.2	1.1
Riboflavin	mg	1.7	1.3	1.1
Niacin	mg	20	16	14
Vitamin B6	mg	2	1.3	1.3
Vitamin B12	μg	6	2.4	2.4
Biotin	mg	0.3	0.03	0.03
Pantothenic acid	mg	10	5	5
Calcium	mg	1000	1000	1000
Phosphorus	mg	1000	700	700
Iodide	μg	150	150	150
Iron	mg	18	8	18
Magnesium	mg	400	400	310
Copper	mg	2	0.9	0.9
Zinc	mg	15	11	8
Sodium	mg	<2400	1500	1500
Potassium	mg	3500	4700	4700
Chloride	mg	3400	2300	2300
Manganese	mg	2	2.3	1.8
Selenium	μg	70	55	55
Chromium	μg	120	35	25
Molybdenum	μg	75	45	45

Note

* Daily values are based on a 2000 kcal diet, with a caloric distribution of 30% from fat (one-third of this total from saturated fat), 60% for carbohydrate, and 10% from protein. They are generally set at the highest nutrient recommendation in a specific age and gender category, and thus many daily values exceed current nutrient standards. g = gram; mg = milligram; μg = microgram; IU = international unit.

Appendix F

World anti-doping code international standard prohibited list

SUBSTANCES AND METHODS PROHIBITED AT ALL TIMES

Prohibited substances

S0-non-approved substances

Any pharmacological substance that is not addressed by any of the subsequent sections of the list and with no current approval by any governmental regulatory health authority for human therapeutic use (e.g., drugs under pre-clinical or clinical development or discontinued, designer drugs, substances approved only for veterinary use) is prohibited at all times.

S1-anabolic agents

1 Anabolic androgenic steroids (AAS)
  a Exogenous AAS, including:

1-androstenediol (5α-androst-1-ene-3β,17β-diol);
1-androstenedione (5α-androst-1-ene-3,17-dione);
1-testosterone (17β-hydroxy-5α-androst-1-en-3-one);
4-hydroxytestosterone (4,17β-dihydroxyandrost-4-en-3-one);
19-norandrostenedione (estr-4-ene-3,17-dione);
Bolandiol (estr-4-ene-3β,17β-diol);
Bolasterone;
Boldenone;
Boldione (androsta-1,4-diene-3,17-dione);
Calusterone;
Clostebol;
Danazol ([1,2]oxazolo[4',5':2,3]pregna-4-en-20-yn-17α-ol);
Dehydrochlormethyltestosterone (4-chloro-17β-hydroxy-17α-methylandrosta-1,4-dien-3-one);
Desoxymethyltestosterone (17α-methyl-5α-androst-2-en-17β-ol);
Drostanolone;
Ethylestrenol (19-norpregna-4-en-17α-ol);
Fluoxymesterone;
Formebolone;
Furazabol (17α-methyl [1,2,5]oxadiazolo[3',4':2,3]-5α-androstan-17β-ol);

Gestrinone;
Mestanolone;
Mesterolone;
Metandienone (17β-hydroxy-17α-methylandrosta-1,4-dien-3-one);
Metenolone;
Methandriol;
Methasterone (17β-hydroxy-2α,17α-dimethyl-5α-androstan-3-one);
Methyldienolone (17β-hydroxy-17α-methylestra-4,9-dien-3-one);
Methyl-1-testosterone (17β-hydroxy-17α-methyl-5α-androst-1-en-3-one);
Methylnortestosterone (17β-hydroxy-17α-methylestr-4-en-3-one);
Methyltestosterone;
Metribolone (methyltrienolone, 17β-hydroxy-17α-methylestra-4,9,11-trien-3-one);
Mibolerone;
Nandrolone;
Norboletone;
Norclostebol;
Norethandrolone;
Oxabolone;
Oxandrolone;
Oxymesterone;
Oxymetholone;
Prostanozol (17β-[(tetrahydropyran-2-yl)oxy]-1'Hpyrazolo[3,4:2,3]-5α-androstane);
Quinbolone;
Stanozolol;
Stenbolone;
Tetrahydrogestrinone (17-hydroxy-18a-homo-19-nor-17α-pregna-4,9,11-trien-3-one);
Trenbolone (17β-hydroxyestr-4,9,11-trien-3-one);
and other substances with a similar chemical structure or similar biological effect(s).

b Endogenous AAS when administered exogenously:

Androstenediol (androst-5-ene-3β,17β-diol);
Androstenedione (androst-4-ene-3,17-dione);
Dihydrotestosterone (17β-hydroxy-5α-androstan-3-one);
Prasterone (dehydroepiandrosterone, DHEA, 3β-hydroxyandrost-5-en-17-one);
Testosterone;

and their metabolites and isomers, including but not limited to:

3β-Hydroxy-5α-androstan-17-one;
5α-Androstane-3α,17α-diol;
5α-Androstane-3α,17β-diol;
5α-Androstane-3β,17α-diol;
5α-Androstane-3β,17β-diol;
5β-Androstane-3α,17β-diol;
7α-Hydroxy-DHEA;
7β-Hydroxy-DHEA;
4-Androstenediol (androst-4-ene-3β, 17β-diol);
5-Androstenedione (androst-5-ene-3,17-dione);

7-Keto-DHEA;
19-Norandrosterone;
19-Noretiocholanolone;
Androst-4-ene-3α,17α-diol;
Androst-4-ene-3α,17β-diol;
Androst-4-ene-3β,17α-diol;
Androst-5-ene-3α,17α-diol;
Androst-5-ene-3α,17β-diol;
Androst-5-ene-3β,17α-diol;
Androsterone;
Epi-dihydrotestosterone;
Epitestosterone;
Etiocholanolone.

2 Other Anabolic Agents
Including, but not limited to: clenbuterol, selective androgen receptor modulators (SARMs, e.g., andarine and ostarine), tibolone, zeranol and zilpaterol.

S2-peptide hormones, growth factors, related substances, and mimetics

The following substances, and other substances with similar chemical structure or similar biological effect(s), are prohibited:

1 Erythropoietin-receptor agonists:
   a Erythropoiesis-stimulating agents (ESAs), including

   - Darbepoietin (dEPO);
   - Erythropoietins (EPO);
   - EPO-Fc;
   - EPO-mimetic peptides (EMP), e.g., CNTO 530 and peginesatide; methoxy polyethylene glycol-epoetin beta (CERA).

   b Non-erythropoietic EPO-receptor agonists, including

   - ARA-290;
   - asialo EPO;
   - carbamylated EPO.

2 Hypoxia-inducible factor (HIF) stabilizers, e.g., cobalt and FG-4592; and HIF activators, e.g., argon, xenon.
3 Chorionic gonadotrophin (CG) and luteinizing hormone (LH) and their releasing factors, e.g., buserelin, gonadorelin and leuprorelin, in males.
4 Corticotrophins and their releasing factors, e.g., corticorelin.
5 Growth hormone (GH) and its releasing factors, including:

   - Growth hormone releasing hormone (GHRH) and its analogues, e.g., CJC-1295, sermorelin and tesamorelin;
   - Growth hormone secretagogues (GHS), e.g., ghrelin and ghrelin mimetics, e.g., anamorelin and ipamorelin;
   - GH-releasing peptides (GHRPs), e.g., alexamorelin, GHRP-6, hexarelin and pralmorelin (GHRP-2).

6 Additional prohibited growth factors:

- Fibroblast growth factor (FGF);
- Hepatocyte growth factor (HGF);
- Insulin-like growth factor-1 (IGF-1) and its analogues;
- Mechano growth factor (MGF);
- Platelet-derived growth factor (PDGF);
- Vascular-endothelial growth factor (VEGF);
- Any other growth factor affecting muscle, tendon, or ligament protein synthesis/degradation, vascularization, energy utilization, regenerative capacity, or fiber type switching.

S3-beta-2 agonists

All beta-2 agonists, including all optical isomers (e.g., d- and l-) where relevant, are prohibited except for:

- Inhaled salbutamol (maximum 1600 micrograms over 24 hours);
- Inhaled formoterol (maximum delivered dose 54 micrograms over 24 hours);
- Inhaled salmeterol in accordance with the manufacturers' recommended therapeutic regimen.

Note: The presence in urine of salbutamol in excess of 1000 ng/mL or formoterol in excess of 40 ng/mL is presumed not to be an intended therapeutic use of the substance and will be considered as an adverse analytical finding (AAF) unless the athlete proves, through a controlled pharmacokinetic study, that the abnormal result was the consequence of the use of the therapeutic inhaled dose up to the maximum indicated above.

S4-hormone and metabolic modulators

The following hormone and metabolic modulators are prohibited:

1 Aromatase inhibitors including, but not limited to:

- 4-androstene-3,6,17 trione (6-oxo);
- Aminoglutethimide;
- Anastrozole;
- Androsta-1,4,6-triene-3,17-dione (androstatrienedione);
- Exemestane;
- Formestane;
- Letrozole;
- Testolactone.

2 Selective estrogen receptor modulators (SERMs) including, but not limited to:

- Raloxifene;
- Tamoxifen;
- Toremifene.

3 Other anti-estrogenic substances including, but not limited to:

- Clomiphene;
- Cyclofenil;
- Fulvestrant.

4 Agents modifying myostatin function(s) including, but not limited to: myostatin inhibitors.
5 Metabolic modulators:

- Activators of the AMP-activated protein kinase (AMPK), e.g., AICAR; and peroxisome proliferator activated receptor δ (PPARδ) agonists, e.g., GW 1516;
- Insulins and insulin-mimetics;
- Meldonium;
- Trimetazidine.

S5-diuretics and masking agents

The following diuretics and masking agents are prohibited, as are other substances with a similar chemical structure or similar biological effect(s) including, but not limited to:

- Desmopressin; probenecid; plasma expanders, e.g., glycerol and intravenous administration of albumin, dextran, hydroxyethyl starch and mannitol;
- Acetazolamide; amiloride; bumetanide; canrenone; chlortalidone; etacrynic acid; furosemide; indapamide; metolazone; spironolactone; thiazides, e.g., bendroflumethiazide, chlorothiazide and hydrochlorothiazide; triamterene and vaptans, e.g., tolvaptan.

Except:

- Drospirenone; pamabrom; and ophthalmic use of carbonic anhydrase inhibitors (e.g., dorzolamide, brinzolamide);
- Local administration of felypressin in dental anesthesia.

Note: The detection in an athlete's sample at all times or in competition, as applicable, of any quantity of the following substances subject to threshold limits: formoterol, salbutamol, cathine, ephedrine, methylephedrine, and pseudoephedrine, in conjunction with a diuretic or masking agent, will be considered as an adverse analytical finding unless the athlete has an approved TUE for that substance in addition to the one granted for the diuretic or masking agent.

Prohibited methods

M1-prohibited methods manipulation of blood and blood components

The following are prohibited:

- The administration or reintroduction of any quantity of autologous, allogenic (homologous) or heterologous blood, or red blood cell products of any origin into the circulatory system.
- Artificially enhancing the uptake, transport, or delivery of oxygen including, but not limited to: perfluorochemicals; efaproxiral (RSR13) and modified hemoglobin products, e.g., hemoglobin-based blood substitutes and microencapsulated hemoglobin products, excluding supplemental oxygen.
- Any form of intravascular manipulation of the blood or blood components by physical or chemical means.

M2-chemical and physical manipulation

The following are prohibited:

- Tampering, or attempting to tamper, to alter the integrity and validity of samples collected during doping control including, but not limited to: urine substitution and/or adulteration, e.g., proteases.
- Intravenous infusions and/or injections of more than 50 mL per 6-hour period except for those legitimately received in the course of hospital admissions, surgical procedures, or clinical investigations.

M3-gene doping

The following, with the potential to enhance sport performance, are prohibited:

- The transfer of polymers of nucleic acids or nucleic acid analogues.
- The use of normal or genetically modified cells.

SUBSTANCES AND METHODS PROHIBITED IN COMPETITION

Prohibited substances

S6-stimulants

All stimulants, including all optical isomers (e.g., d- and l-) where relevant, are prohibited.
Stimulants include:

a Non-specified stimulants:
Adrafinil;
Amfepramone;
Amfetamine;
Amfetaminil;
Amiphenazole;
Benfluorex;
Benzylpiperazine;
Bromantan;
Clobenzorex;
Cocaine;
Cropropamide;
Crotetamide;
Fencamine;
Fenetylline;
Fenfluramine;
Fenproporex;
Fonturacetam [4-phenylpiracetam (carphedon)];
Furfenorex;
Mefenorex;
Mephentermine;
Mesocarb;
Metamfetamine(d-);
p-methylamphetamine;

Modafinil;
Norfenfluramine;
Phendimetrazine;
Phentermine;
Prenylamine;
Prolintane.

Note: A stimulant not expressly listed in this section is a specified substance.

b Specified stimulants.
Including, but not limited to:

- Benzfetamine;
- Cathine**;
- Cathinone and its analogues, e.g., mephedrone, methedrone, and α-pyrrolidinovalerophenone;
- Dimethylamphetamine;
- Ephedrine***;
- Epinephrine**** (adrenaline);
- Etamivan;
- Etilamfetamine;
- Etilefrine;
- Famprofazone;
- Fenbutrazate;
- Fencamfamin;
- Heptaminol;
- Hydroxyamfetamine (parahydroxyamphetamine);
- Isometheptene;
- Levmetamfetamine;
- Meclofenoxate;
- Methylenedioxymethamphetamine;
- Methylephedrine***;
- Methylhexaneamine (dimethylpentylamine);
- Methylphenidate;
- Nikethamide;
- Norfenefrine;
- Octopamine;
- Oxilofrine (methylsynephrine);
- Pemoline;
- Pentetrazol;
- Phenethylamine and its derivatives;
- Phenmetrazine;
- Phenpromethamine;
- Propylhexedrine;
- Pseudoephedrine*****;
- Selegiline;
- Sibutramine;
- Strychnine;
- Tenamfetamine (methylenedioxyamphetamine);
- Tuaminoheptane;
- Other substances with a similar chemical structure or similar biological effect(s).

Except:

- Clonidine;
- Imidazole derivatives for topical/ophthalmic use and those stimulants included in the 2016 Monitoring Program*.

Notes

* *Bupropion, caffeine, nicotine, phenylephrine, phenylpropanolamine, pipradrol, and synephrine. These substances are included in the 2016 Monitoring Program, and are not considered prohibited substances.*

** *Cathine: Prohibited when its concentration in urine is greater than 5 micrograms per milliliter.*

*** *Ephedrine and methylephedrine: Prohibited when the concentration of either in urine is greater than 10 micrograms per milliliter.*

**** *Epinephrine (adrenaline): Not prohibited in local administration, e.g., nasal, ophthalmologic, or co-administration with local anaesthetic agents.*

***** *Pseudoephedrine: Prohibited when its concentration in urine is greater than 150 micrograms per milliliter.*

S7-narcotics

Prohibited:

- Buprenorphine;
- Dextromoramide;
- Diamorphine (heroin);
- Fentanyl and its derivatives;
- Hydromorphone;
- Methadone;
- Morphine;
- Oxycodone;
- Oxymorphone;
- Pentazocine;
- Pethidine.

S8-cannabinoids

Prohibited:

- Natural, e.g., cannabis, hashish and marijuana, or synthetic Δ9-tetrahydrocannabinol (THC);
- Cannabimimetics, e.g., "Spice," JWH-018, JWH-073, HU-210.

S9-glucocorticoids

All glucocorticoids are prohibited when administered by oral, intravenous, intramuscular, or rectal routes.

SUBSTANCES PROHIBITED IN PARTICULAR SPORTS

P1-alcohol

Alcohol (ethanol) is prohibited in competition only in the following sports. Detection will be conducted by analysis of breath and/or blood. The doping violation threshold is equivalent to a blood alcohol concentration of 0.10 g/L.

- Air sports (FAI);
- Automobile (FIA);
- Archery (WA);
- Powerboating (UIM).

P2-beta-blockers

Beta-blockers are prohibited in competition only, in the following sports, and also prohibited out of competition where indicated.

- Archery (WA)*;
- Automobile (FIA);
- Billiards (all disciplines) (WCBS);
- Darts (WDF);
- Golf (IGF);
- Shooting (ISSF, IPC)*;
- Skiing/Snowboarding (FIS) in ski jumping, freestyle aerials/halfpipe, and snowboard halfpipe/big air;
- Underwater sports (CMAS) in constant-weight apnea with or without fins, dynamic apnea with and without fins, free immersion apnea, Jump Blue apnea, spearfishing, static apnea, target shooting, and variable weight apnea.

*Note: *Also prohibited out of competition.*

The beta-blockers including, but not limited to:

- Acebutolol;
- Alprenolol;
- Atenolol;
- Betaxolol;
- Bisoprolol;
- Bunolol;
- Carteolol;
- Carvedilol;
- Celiprolol;
- Esmolol;
- Labetalol;
- Levobunolol;
- Metipranolol;
- Metoprolol;
- Nadolol;
- Oxprenolol;
- Pindolol;
- Propranolol;
- Sotalol;
- Timolol.

Appendix G

Directions for conducting three-day dietary analysis

Step 1: completing food records/diary

1 Select one weekend day and two weekdays that are most reflective of your usual eating patterns.
2 Record one food item per line in the recording sheet (see below).
3 Include brand names whenever possible.
4 Record amounts in household measures, such as ounce, tablespoon, cup, slice, or unit.
5 Read food labels and, if possible, use standard measuring tools, such as plastic ruler, measuring cup, measuring spoons, and weighing scale.
6 Include methods that were used to prepare food items, such as fresh, frozen, stewed, fried, baked, canned, broiled, raw, or braised.
7 Record the amounts of visible fats you eat or use in cooking, such as oils, butter, salad dressing, margarine.
8 Keep your food diary current, and list foods immediately after they are eaten.
9 Do not alter your normal diet during the period you keep this diary.

Step 2: analyzing nutrient intakes using a computer program "nutritioncalc plus"

1 Getting started:

- Upon installation, select NutritionCalc Plus from your program files.
- Be sure to enter your name and course information in the student ID information box. This information will be printed at the top of each of your report pages.
- To begin your personal diet analysis, click on the Profiles tab. Simply complete each section and move to the next tab as indicated in your assignment. Note that each tabbed section will have a drop-down information box on the top right of your screen. Click on the triangle to use the drop-down to learn about the purpose of each tabbed section.

2 Creating a new profile:

- On the Profiles tab, click New.
- Enter the following information:
  - Name: Enter name.
  - Birth date: Enter birthday as month/day/year. Example: 12/08/1987.
  - Gender: Select gender from the pull-down list.
  - Height: Enter height in English or metric units.
  - Weight: Enter current weight in pounds or kilograms.

3 Calculating weight gain/loss:

- To calculate the calorie change per week or duration needed to reach your goal, click Weight gain/loss.
- The current weight you entered will be shown. Enter your goal weight. Select Calorie change (per day) or Duration (in weeks) and enter a value. Choose Calculate button and the program will fill in the remaining values. A safe weight change per week is less than 2 lb.

> ***Example:*** *Current weight = 165. Goal weight = 145. Select Duration and enter 20 (weeks). Click Calculate. The program calculates the weight change value as 20 and the Calorie change per day as –375.*

4 Activity level

- Select Activity level from pull-down menu that best matches your individual activity level. For a description of each level, click the link. The Activity level is a way to estimate the Calories needed every day to maintain current weight.

> ***Activity level descriptions***
>
> *Sedentary*
>
> *The sedentary activity level includes activities of daily living, without additional exercise. These activities include housework, grocery shopping, walking the dog, walking to the bus, mowing the lawn, and gardening. Unless you do at least 30 minutes per day of intentional exercise, this level is for you!*
>
> *Low active*
>
> *The low active activity level includes activities of daily living plus exercise that is equal to walking for 30 minutes at 4 miles per hour every day. For an adult of average weight, this amount of exercise will burn about 120 additional calories. Exercises with lower intensity (METS*) will need to be performed longer to burn the same amount of calories. Likewise, exercises with more intensity may be performed for less time to achieve the same goal.*
>
> *Active*
>
> *The active activity level includes activities of daily living plus exercise that is equal to walking for 1 hour 45 minutes at 4 miles per hour every day. For an adult of average weight, this amount of exercise will burn about 410 additional calories.*
>
> *Very active*
>
> *The very active activity level includes activities of daily living plus exercise that is equal to walking for 4 hours 15 minutes at 4 miles per hour every day. For an adult of average weight, this amount of exercise will burn about 1000 additional calories.*
>
> - After entering all information, click Save profile.
> - Note that the active profile name will appear in the Profile box in the upper right of the screen.

5 Intakes

- Intakes are made up of the food consumed in one day. Each food item will be part of a meal: breakfast, dinner, lunch, or snack. You can track intakes for as many days as you like; there is no limit.
- When the Intake page opens for the first time it will open to today's date and you can begin entering food items consumed on that day. If you wish to enter foods for a different day, simply click on the date. That day will be the active day and will be highlighted in orange. After you enter more than one day's worth of intakes, the previous days with intakes will be shaded in green.
- To create a new intake click on the Intake tab. Follow the instructions on the screen to search for foods to add to your intake list. To create an intake for a different date, use the 365-day calendar to select the appropriate date.
- To search for and enter a food item, type the search term or terms in the search box and click on Find. The results will show each item available that meets the search criteria.

Search tips

Single word search

Enter one word to find all items that contain that word in the name.

Multiple word search

Enter two or more words to find all items that contain all the words in the name. The words can appear anywhere in the name and in any order.

Grouping

Enclosing the words in quotation marks will find all items that contain that exact phrase. For example, entering "Fried chicken" will find all items that contain "Fried chicken," but NOT "Chicken, fried" or "Fried potatoes and chicken."

Wildcard

Type in a partial word followed by an asterisk. The results will include any item beginning with the partial word. For example, if you type in "mil" you will get millet, milk, etc.*

NOT or – (minus) search

The search will eliminate items that contain the term after NOT or –. For example, searching for chocolate NOT milk will return items with chocolate but not milk in the title.

OR search

Typing OR between search terms will give you a search list with either of those terms in the title. For example, typing chocolate OR milk will give you all items with chocolate in their name and all items with milk in their name.

- Select the food from the search results list and click on the Plus (+) button to add the food to your intake.
- Click the item name link to preview the item. To add the item to your intake from the preview page, click the plus sign at the top.
- When the item has been added to your intake, select the Meal and serving amount in the drop-down.

- Click Save intake after each entry.
- Continue adding the remaining items in the same manner.
- To assist in searching, check out the Search tips and list of common abbreviations used in the food database. The Fast entry function automatically saves your last 20 food entries. Use this function to quickly compile your food list using foods you eat or drink on a regular basis. Click on Fast entry and place check marks in the box to the left of the foods you wish to add to your intake list.

Table G.1 Sample recording sheet

Food/method of preparation	*Quantity*	*Meal*	*Note*

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