to relax. As the feces are forced through the anal canal, messages reach the brain giving us time to decide whether the external voluntary sphincter should remain open or be constricted to stop passage of feces. If it is not convenient, defecation (or "moving the bowels") can be delayed temporarily. Within a few seconds, the reflex contractions end, and the rectal walls relax. With the next mass movement, the defecation reflex is initiated again.

Homeostatic Imbalance 14.10

Watery stools, or **diarrhea** (di″ah-re′ah), result from any condition that rushes food residue through the large intestine before that organ has had sufficient time to absorb the water (as in irritation of the colon by bacteria). Because fluids and ions are lost from the body, prolonged diarrhea may result in dehydration and electrolyte imbalance which, if severe, can be fatal.

If food residue remains in the large intestine for extended periods, too much water is absorbed, and the stool becomes hard and difficult to pass. This condition, called **constipation,** may result from lack of fiber in the diet, poor bowel habits ("failing to heed the call"), and laxative abuse. ✚

Did You Get It?

17. *What are the building blocks (and digestion products) of proteins?*
18. *What is the role of CCK in digestion?*
19. *What are brush border enzymes?*

(For answers, see Appendix D.)

PART II: NUTRITION AND METABOLISM

14-14 Define *nutrient* and *kilocalorie*.

14-15 List the six nutrient categories. Note important dietary sources and their main cellular uses.

Although it seems at times that people can be divided into two camps—those who live to eat and those who eat to live—we all recognize the vital importance of food for life. It has been said that "you are what you eat," and this is true in that part of the food we eat is converted to our living flesh. In other words, a certain fraction of nutrients is used to build cellular molecules and structures and to replace worn-out parts. However, most foods are used as metabolic fuels. That is, they are oxidized and transformed into **adenosine triphosphate (ATP),** the chemical energy form needed by body cells to drive their many activities. The energy value of foods is measured in units called **kilocalories (kcal),** or Calories (with a capital C), the units conscientiously counted by dieters.

We have just considered how foods are digested and absorbed. But what happens to these foods once they enter the blood? Why do we need bread, meat, and fresh vegetables? Why does everything we eat seem to turn to fat? We will try to answer these questions in this section.

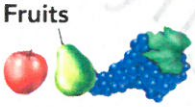
Nutrition

A **nutrient** is a substance in food that is used by the body to promote normal growth, maintenance, and repair. The nutrients divide neatly into six categories. The **major nutrients**—carbohydrates, lipids, and proteins—make up the bulk of what we eat. **Minor nutrients**—vitamins and minerals—while equally crucial for health, are required in minute amounts. Water, which accounts for about 60 percent of the volume of the food we eat, is also considered to be a major nutrient. However, because we described its importance as a solvent and in many other aspects of body functioning in the chapter on basic chemistry (Chapter 2), we will consider only the other five classes of nutrients here.

Most foods offer a combination of nutrients. For example, a bowl of cream of mushroom soup contains all of the major nutrients plus some vitamins and minerals. A diet consisting of foods selected from each of the five food groups (Table 14.2, p. 488), that is, grains, fruits, vegetables, meats and meat alternatives, and milk products, normally guarantees adequate amounts of all of the needed nutrients.

More detailed are the several types of food guide pyramids that have been developed. The version issued in 1992 by Walter Willett, called the **Healthy Eating Pyramid** (Figure 14.17a, p. 489), looks at six major food groups, subdividing some of them further. It uses the traditional (horizontal) orientation of food groups; emphasizes eating whole-grain foods and lots of fruits and vegetables; and recommends substituting plant oils for

Table 14.2 Five Basic Food Groups and Some of Their Major Nutrients

		Major nutrients supplied in significant amounts	
Group	**Example foods**	**By all in group**	**By only some in group**
Fruits 	Apples, bananas, dates, oranges, tomatoes	Carbohydrate Water	Vitamins: A, C, folic acid Minerals: iron, potassium Fiber
Vegetables 	Broccoli, cabbage, green beans, lettuce, potatoes	Carbohydrate Water	Vitamins: A, C, E, K, and B vitamins except B_{12} Minerals: calcium, magnesium, iodine, manganese, phosphorus Fiber
Grain products (preferably whole grain; otherwise, enriched or fortified) 	Breads, rolls, bagels; cereals, dry and cooked; pasta; rice, other grains; tortillas, pancakes, waffles; crackers; popcorn	Carbohydrate Protein Vitamins: thiamine (B_1), niacin	Water Fiber Minerals: iron, magnesium, selenium
Milk products 	Milk, yogurt; cheese; ice cream, ice milk, frozen yogurt	Protein Fat Vitamins: riboflavin, B_{12} Minerals: calcium, phosphorus Water	Carbohydrate Vitamins: A, D
Meats and meat alternatives 	Meat, fish, poultry; eggs; seeds; nuts, nut butters; soybeans, tofu; other legumes (peas and beans)	Protein Vitamins: niacin, B_6 Minerals: iron, zinc	Carbohydrate Fat Vitamins: B_{12}, thiamine (B_1) Water Fiber

animal fats and restricting red meat, sweets, and starchy foods.

Fresh out of the oven in 2011 is **MyPlate,** a food guide with a completely new symbol—a round dinner plate. Issued by the United States Department of Agriculture (USDA), it shows food categories in healthy proportions in sections of a place setting rather than as segments of a pyramid (Figure 14.17). Occupying half the plate are fruits and vegetables (more vegetable than fruit). The other half shows grains and proteins (more grain than protein). A glass represents dairy, the fifth food group. Links provide details on healthy choices in each food group. You can personalize your MyPlate diet by age, sex, and activity level by going to the MyPlate website (www.choosemyplate.gov).

Nutrition advice is constantly in flux and often mired in the self-interest of food companies. Nonetheless, basic dietary principles have not changed in years and are not in dispute: Eat less overall; eat plenty of fruits, vegetables, and whole grains; avoid junk food; and exercise regularly.

Dietary Sources of the Major Nutrients

Carbohydrates

Except for milk sugar (lactose) and small amounts of glycogen in meats, all the **carbohydrates**—sugars and starches—we ingest are derived from plants. Sugars come mainly from fruits, sugar cane, and milk. The polysaccharide starch is found in grains, legumes, and root vegetables. The polysaccharide cellulose, which is plentiful in most vegetables, is not digested by humans, but it provides roughage, or fiber, which increases the bulk of the stool and aids defecation.

Lipids

Although we also ingest cholesterol and phospholipids, most dietary **lipids** are triglycerides (**neutral fats**). We eat saturated fats in animal products such as meat and dairy foods and in a few plant products, such as coconut. Unsaturated fats are present in seeds, nuts, and most vegetable oils. Major sources of cholesterol are egg yolk, meats, and milk products.

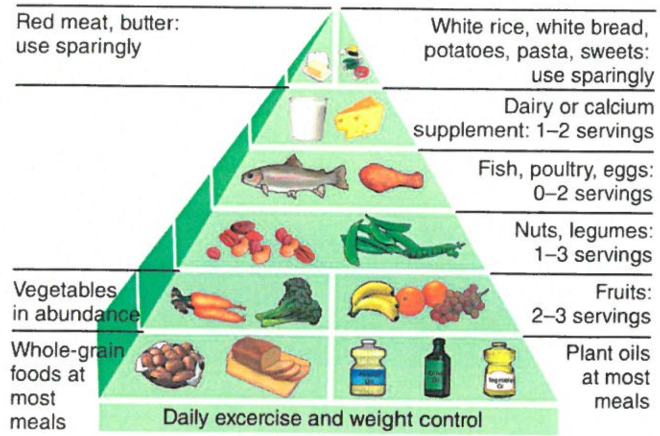
Proteins

Animal products contain the highest-quality **proteins,** molecules that are basically amino acid polymers. Eggs, milk, fish, and most meat proteins are *complete proteins* that meet all of the body's amino acid requirements for tissue maintenance and growth.

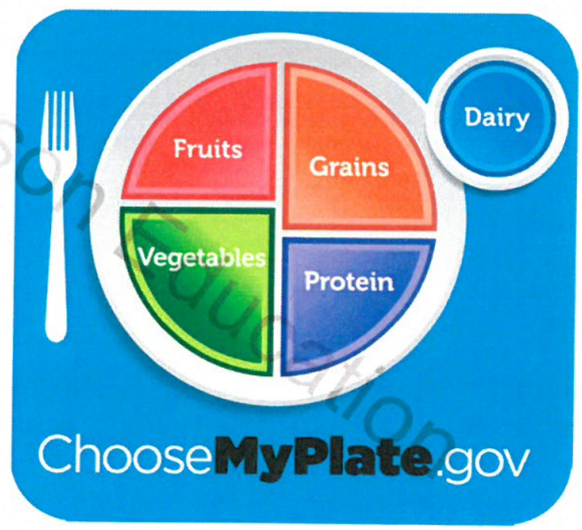
Legumes (beans and peas), nuts, and cereals are also protein-rich, but their proteins are nutritionally incomplete because they are low in one or more of the essential amino acids. The **essential amino acids** are the eight amino acids (listed in Figure 14.18, p. 490), that our body cannot make. Hence we must take these amino acids in through the diet. As you can see, strict vegetarians must carefully plan their diets to obtain all the essential amino acids and prevent protein malnutrition. Cereal grains and legumes when ingested together provide all the needed amino acids, and some variety of this combination is found in the diets of all cultures (most obviously in the rice and beans seen on nearly every plate in a Mexican restaurant).

Vitamins

Vitamins are organic nutrients of various forms that the body requires in small amounts. Although vitamins are found in all major food groups, no one food contains all the required vitamins. Thus, a balanced diet is the best way to ensure a full vitamin complement, particularly because certain



(a) Healthy Eating Pyramid



(b) USDA's MyPlate

Figure 14.17 **Two visual food guides.**

vitamins (A, C, and E) appear to have anticancer effects. Diets rich in broccoli, cabbage, and brussels sprouts (all good sources of vitamins A and C) appear to reduce cancer risk. However, controversy abounds concerning the ability of vitamins to work wonders.

Most vitamins function as **coenzymes** (or parts of coenzymes); that is, they act with an enzyme to accomplish a particular type of catalysis.

Minerals

The body also requires adequate supplies of seven **minerals** (that is, inorganic substances including calcium, phosphorus, potassium, sulfur, sodium, chloride, and magnesium) and trace amounts of about a dozen others.

14

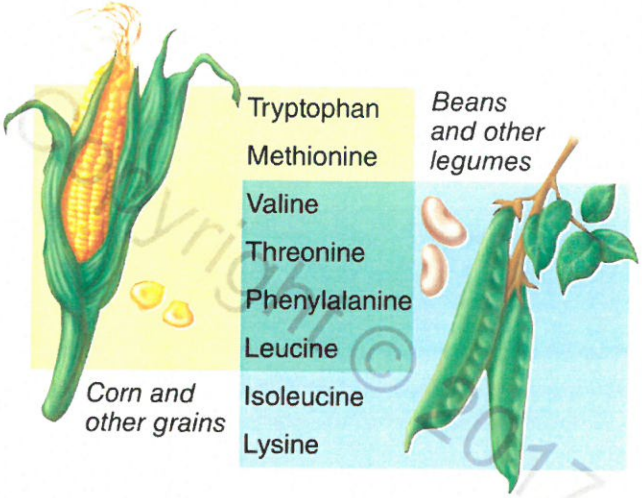


Figure 14.18 The eight essential amino acids. Vegetarian diets must be carefully constructed to provide all essential amino acids. A meal of corn and beans fills the bill: Corn provides the essential amino acids not in beans and vice versa.

Fats and sugars have practically no minerals, and cereals and grains are poor sources. The most mineral-rich foods are vegetables, legumes, milk, and some meats.

The section on metabolism discusses the main uses of the major nutrients in the body. (Appendix C details some important roles of vitamins and minerals in the body.)

Did You Get It?

20. *What is the major source of carbohydrates in our diet?*
21. *Why is it important to include cellulose in a healthy diet even though we cannot digest it?*
22. *Are oils saturated lipids or unsaturated lipids?*
23. *What is the most significant role that vitamins play in the body?*

(For answers, see Appendix D.)

Metabolism

14-16 Define *metabolism, anabolism,* and *catabolism.*

14-17 Recognize the uses of carbohydrates, fats, and proteins in cell metabolism.

Metabolism (mĕ-tab′o-lizm; *metabol* = change) is a broad term referring to all chemical reactions that are necessary to maintain life. It involves **catabolism** (kah-tab′o-lizm), the breakdown of substances to simpler substances, and **anabolism** (ah-nab′o-lizm), the building of larger molecules or structures from smaller ones. During catabolism, bond energy of foods is released and captured to make ATP, the energy-rich molecule used to energize all cellular activities, including catabolic reactions.

Carbohydrate, Fat, and Protein Metabolism in Body Cells

Not all foodstuffs are treated in the same way by body cells. For example, carbohydrates, particularly glucose, are usually broken down to make ATP. Fats are used to build cell membranes, make myelin sheaths, and insulate the body with a fatty cushion. They are also used as the body's main energy fuel for making ATP when there are inadequate carbohydrates in the diet. Proteins tend to be carefully conserved (even hoarded) by the body cells. This is easy to understand when you recognize that proteins are the major structural materials used for building cell structures.

Carbohydrate Metabolism

Just as an oil furnace uses oil (its fuel) to produce heat, the cells of the body use carbohydrates as their preferred fuel to produce cellular energy (ATP). **Glucose,** also known as **blood sugar,** is the major breakdown product of carbohydrate digestion. Glucose is also the major fuel used for making ATP in most body cells. The liver is an exception; it routinely uses fats as well, thus saving glucose for other body cells. Essentially, glucose is broken apart piece by piece, and some of the chemical energy released when its bonds are broken is captured and used to bind phosphate to ADP molecules to make ATP.

Basically, the carbon atoms released leave the cells as carbon dioxide, and the hydrogen atoms removed (which contain energy-rich electrons) are eventually combined with oxygen to form water. (The overall reaction is summed up simply in Figure 14.19.) These oxygen-using events are referred to collectively as **cellular respiration.** The events of the three main metabolic pathways involved in cellular respiration are *glycolysis,* the *Krebs cycle,* and the *electron transport chain* (shown schematically in Figure 14.20).

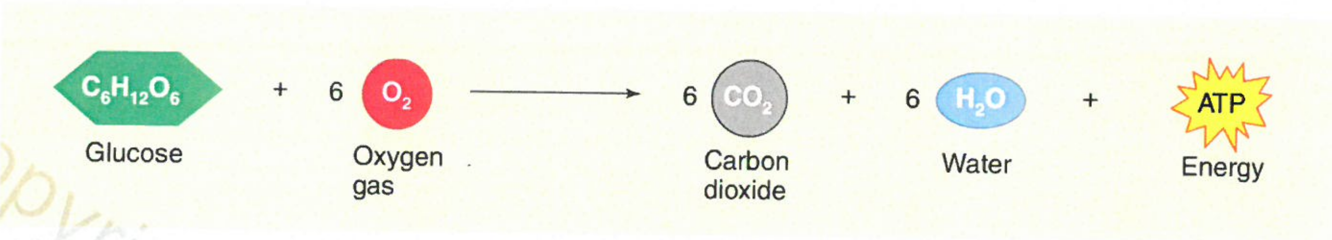
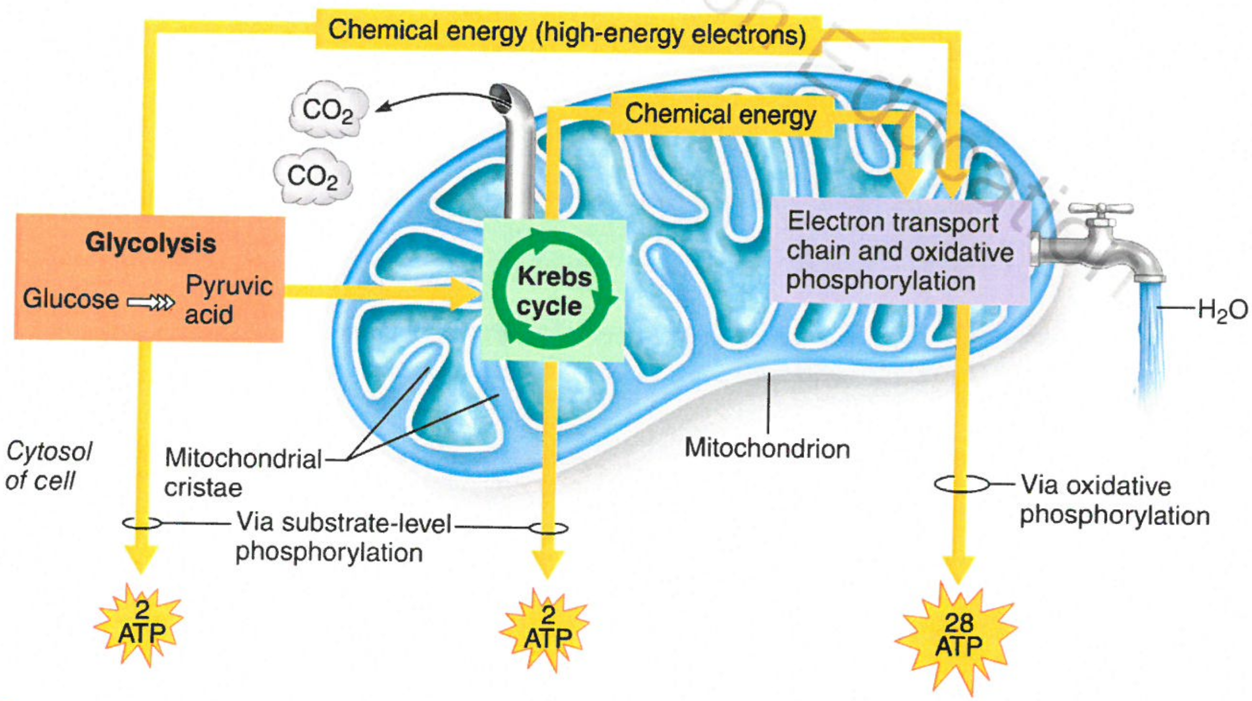


Figure 14.19 Summary equation for cellular respiration.

Oxidation via the removal of hydrogen atoms (which are temporarily passed to vitamin-containing coenzymes) is a major role of glycolysis and the Krebs cycle. **Glycolysis,** which takes place in the cytosol, also energizes each glucose molecule so that it can be split into two pyruvic acid molecules and yield a small amount of ATP in the process (Figure 14.20).

The **Krebs cycle** occurs in the mitochondria and produces virtually all the carbon dioxide that results during cell respiration. Like glycolysis, it yields a small amount of ATP by transferring high-energy phosphate groups directly from phosphorylated substances to ADP, a process called *substrate-level phosphorylation.* Free oxygen is not involved.



(1) During glycolysis, each glucose molecule is broken down into two molecules of pyruvic acid as hydrogen atoms containing high-energy electrons are removed.

(2) The pyruvic acid enters the mitochondrion, where Krebs cycle enzymes remove more hydrogen atoms and decompose it to CO_2. During glycolysis and the Krebs cycle, small amounts of ATP are formed.

(3) Energy-rich electrons picked up by coenzymes are transferred to the electron transport chain, built into the cristae membrane. The electron transport chain carries out oxidative phosphorylation, which accounts for most of the ATP generated by cellular respiration, and finally unites the removed hydrogen with oxygen to form water.

Figure 14.20 During cellular respiration, ATP is formed in the cytosol and in the mitochondria. The maximum energy yield per glucose molecule is 32 ATP.

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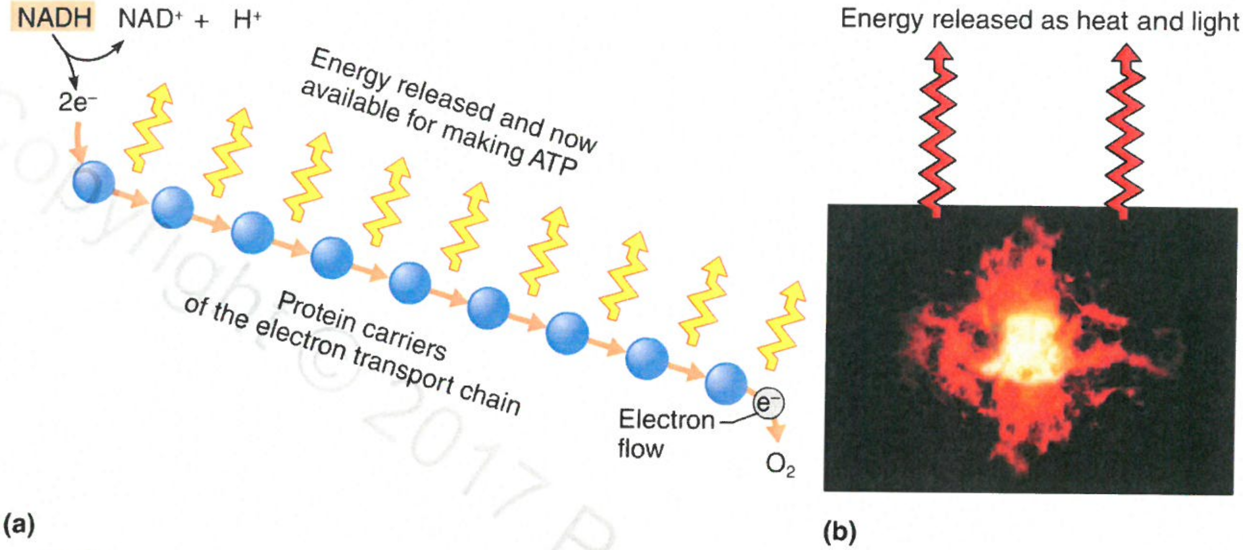

Figure 14.21 Electron transport chain versus one-step reduction of oxygen. (a) In cellular respiration, cascading electrons release energy in small steps and finally reduce O_2 and form water. The energy released is in quantities easily used to form ATP. (NADH is a niacin-containing coenzyme that delivers H^+ to the electron transport chain.) **(b)** When O_2 is reduced (combined with hydrogen) in one step, the result is an explosion.

The **electron transport chain** is where the action is for ATP production. The hydrogen atoms removed during the first two metabolic phases are loaded with energy. These hydrogens are delivered by the coenzymes to the protein carriers of the electron transport chain, which form part of the mitochondrial cristae membranes (Figure 14.21a). There the hydrogen atoms are split into hydrogen ions (H^+) and electrons (e^-). The electrons "fall down an energy hill" going from each carrier to a carrier of lower energy. They give off their "load" of energy in a series of steps in small enough amounts to enable the cell to attach phosphate to ADP and make ATP. Ultimately, free oxygen is reduced (the electrons and hydrogen ions are united with molecular oxygen), forming water and a large amount of ATP. This more complicated process of ATP formation is called *oxidative phosphorylation*. The beauty of this system is that, unlike the explosive reaction (Figure 14.21b) that usually happens when fuels are burned (O_2 is combined with hydrogen), relatively small amounts of energy are lost as heat (and light).

Because glucose is the major fuel for making ATP, homeostasis of blood glucose levels is critically important. If there are excessively high levels of glucose in the blood (**hyperglycemia** [hi″per-gli-se′me-ah]), some of the excess is stored in body cells (particularly liver and muscle cells) as glycogen. If blood glucose levels are still too high, excesses are converted to fat. There is no question that eating large amounts of empty-calorie foods such as candy and other sugary sweets causes a rapid deposit of fat in the body's adipose tissues. When blood glucose levels are too low **(hypoglycemia),** the liver breaks down stored glycogen and releases glucose to the blood for cellular use. (These various fates of carbohydrates are shown in Figure 14.22a.)

Did You Get It?

24. *What name is given to the process in which glucose is combined with oxygen to yield CO_2, H_2O, and ATP?*
25. *What are the major end products of the Krebs cycle?*
26. *What are the major products of the electron transport chain?*

(For answers, see Appendix D.)

Fat Metabolism

As we will describe shortly, the liver handles most lipid, or fat, metabolism that goes on in the body. The liver cells use some fats to make ATP for their own use; use some to synthesize lipoproteins,

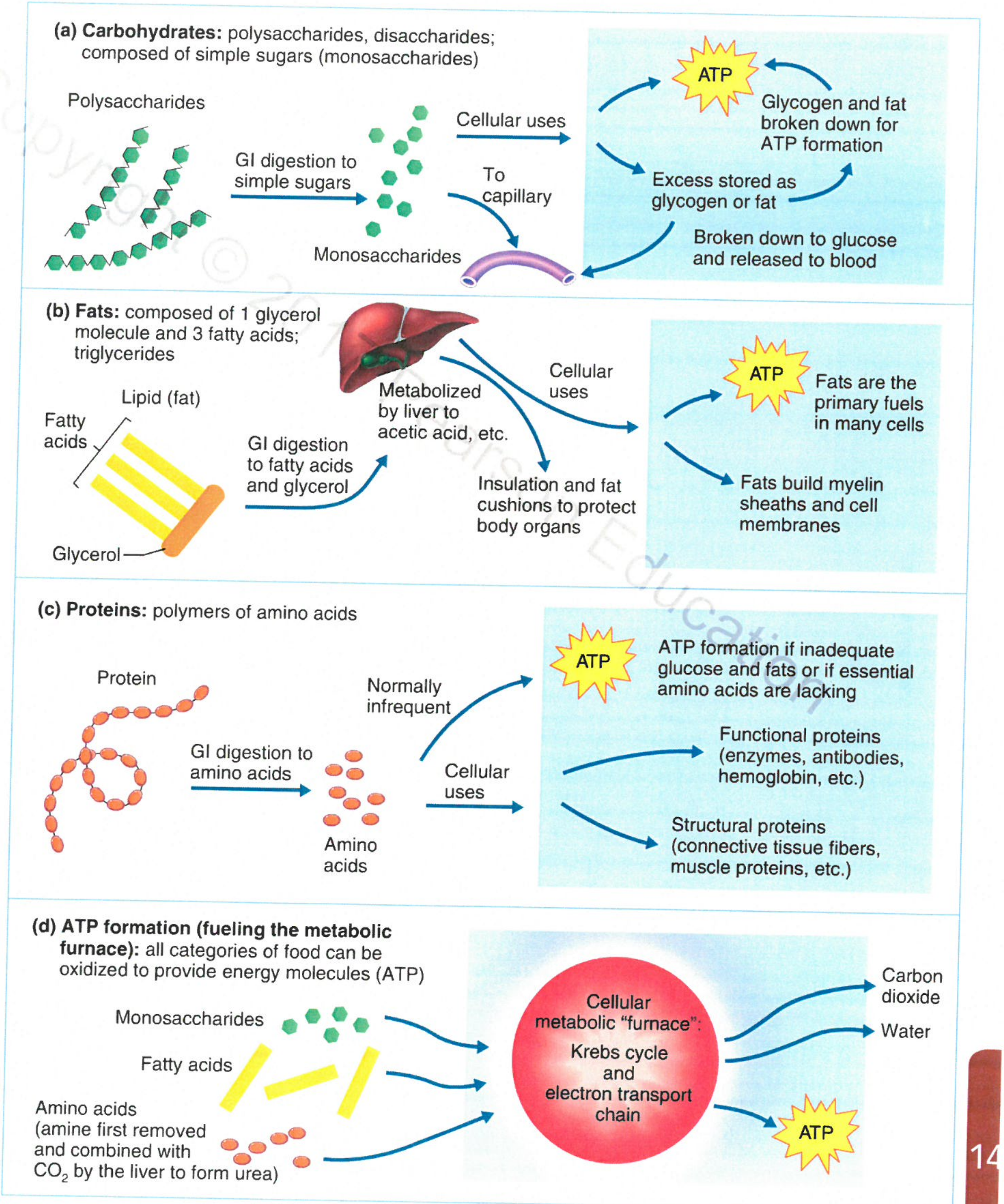

Figure 14.22 Metabolism by body cells. **(a)** Carbohydrate metabolism. **(b)** Fat metabolism. **(c)** Protein metabolism. **(d)** ATP formation.

thromboplastin (a clotting protein), and cholesterol; and then release the rest to the blood in the form of relatively small fat-breakdown products. Body cells remove the fat products and cholesterol from the blood and build them into their membranes or steroid hormones as needed. Fats are also used to form myelin sheaths of neurons (see Chapter 7) and fatty cushions around body organs. In addition, stored fats are the body's most concentrated source of energy. (Catabolism of 1 gram of fat yields twice as much energy as the breakdown of 1 gram of carbohydrate or protein.)

For fat products to be used for ATP synthesis, they must first be broken down to acetic acid (Figure 14.22b). Within the mitochondria, the acetic acid (like the pyruvic acid product of carbohydrates) is then completely oxidized, and carbon dioxide, water, and ATP are formed.

When there is not enough glucose to fuel the needs of the cells for energy, larger amounts of fats are used to produce ATP. Under such conditions, fat oxidation is fast but incomplete, and some of the intermediate products, such as acetoacetic acid and acetone, begin to accumulate in the blood. These cause the blood to become acidic (a condition called **acidosis,** or **ketoacidosis**), and the breath takes on a fruity odor as acetone diffuses from the lungs. Ketoacidosis is a common consequence of "no-carbohydrate" diets, uncontrolled diabetes mellitus, and starvation in which the body is forced to rely almost totally on fats to fuel its energy needs. Although fats are an important energy source, cholesterol is *never* used as a cellular fuel. Its importance lies in the functional molecules and in the structures it helps to form.

Excess fats are stored in fat depots such as the hips, abdomen, breasts, and subcutaneous tissues. Although the fat in subcutaneous tissue is important as insulation for the deeper body organs, excessive amounts restrict movement and place greater demands on the circulatory system. (The metabolism and uses of fats are shown in Figure 14.22b.)

Protein Metabolism

Proteins make up the bulk of cellular structures, and they are carefully conserved by body cells. Ingested proteins are broken down to amino acids. Once the liver has finished processing the blood draining the digestive tract and has taken its "fill" of amino acids, the remaining amino acids circulate to the body cells. The cells remove amino acids from the blood and use them to build proteins, both for their own use (enzymes, membranes, mitotic spindle proteins, muscle proteins) and for export (mucus, hormones, and others). Cells take few chances with their amino acid supply. They use ATP to actively transport amino acids into their interior even though in many cases they may contain more of those amino acids than are in the blood flowing past them. Even though this may appear to be "cellular greed," there is an important reason for this active uptake of amino acids. Cells cannot build their proteins unless *all* the needed amino acids, which number around 20, are present. As mentioned earlier, because cells cannot make the essential amino acids, they are available to the cells only through the diet. This helps explain the avid accumulation of amino acids, which ensures that all amino acids needed will be available for present and (at least some) future protein-building needs of the cells (Figure 14.22c).

Amino acids are used to make ATP only when proteins are overabundant and/or when carbohydrates and fats are not available. When it is necessary to oxidize amino acids for energy (Figure 14.22d), their amine groups are removed as *ammonia,* and the rest of the molecule enters the Krebs cycle pathway in the mitochondria.

The ammonia that is released during this process is toxic to body cells, especially nerve cells. The liver comes to the rescue by combining the ammonia with carbon dioxide to form **urea** (u-re'ah). Urea, which is not harmful to the body cells, is then flushed from the body in urine.

Did You Get It?

27. *Other than for ATP production, list two uses of fats in the body.*

28. *What happens to the ammonia released when amino acids are "burned" for energy?*

(For answers, see Appendix D.)

The Central Role of the Liver in Metabolism

14-18 Describe the metabolic roles of the liver.

The liver is one of the most versatile and complex organs in the body. Without it, we would die within 24 hours. Its role in digestion (that is, the manufacture of bile) is important to the digestive process to be sure, but it is only one of the many functions of liver cells. The liver cells detoxify drugs and alcohol, degrade hormones, and make many substances vital to the body as a whole (cholesterol, blood proteins such as albumin and clotting proteins, and lipoproteins). They play a central role in metabolism as they process nearly every class of nutrient. Because of the liver's key roles, nature has provided us with a surplus of liver tissue. We have much more than we need, and even if part of it is damaged or removed, it is one of the few body organs that can regenerate rapidly and easily.

A unique circulation, the *hepatic portal circulation,* brings nutrient-rich blood draining from the digestive viscera directly to the liver (see Chapter 11). The liver is the body's major metabolic organ, and this detour that nutrients take through the liver ensures that the liver's needs will be met first. As blood circulates slowly through the liver, liver cells remove amino acids, fatty acids, and glucose from the blood. These nutrients are stored for later use or processed in various ways. At the same time, the liver's phagocytic cells remove and destroy bacteria that have managed to get through the walls of the digestive tract and into the blood.

General Metabolic Functions

The liver is vitally important in helping to maintain blood glucose levels within normal range (around 100 mg glucose/100 ml of blood). After a carbohydrate-rich meal, thousands of glucose molecules are removed from the blood and combined to form the large polysaccharide molecules called **glycogen** (gli′ko-jen), which are then stored in the liver. This process is **glycogenesis** (gli″ko-jen′ĕ-sis), literally, "glycogen formation" (*genesis* = beginning).

Later, as body cells continue to remove glucose from the blood to meet their needs, blood glucose levels begin to drop. At this time, liver cells break down the stored glycogen by a process called **glycogenolysis** (gli″ko-jen-ol′ĭ-sis), which means "glycogen splitting." The liver cells then release glucose bit by bit to the blood to maintain homeostasis of blood glucose levels.

If necessary, the liver can also make glucose from noncarbohydrate substances, such as fats and proteins. This process is **gluconeogenesis** (glu″ko-ne″o-jen′ĕ-sis), which means "formation of new sugar" (**Figure 14.23**, p. 496). Hormones such as thyroxine, insulin, and glucagon are vitally important in controlling the blood sugar levels and in the handling of glucose in all body cells (see Chapter 9).

Some of the fats and fatty acids picked up by the liver cells are oxidized for energy (to make ATP) for use by the liver cells themselves. The rest are broken down to simpler substances such as *acetic acid* and *acetoacetic acid* (two acetic acids linked together) and released into the blood or are stored as fat reserves in the liver. The liver also makes cholesterol and secretes cholesterol's breakdown products in bile.

All blood proteins made by the liver are built from the amino acids its cells pick up from the blood. The completed proteins are then released back into the blood to travel throughout the circulation. *Albumin,* the most abundant protein in blood, holds fluids in the bloodstream. When insufficient albumin is present in blood, fluid leaves the bloodstream and accumulates in the tissue spaces, causing edema. (In Chapter 10, we discussed the role of the protective *clotting proteins* made by the liver.) Liver cells also synthesize nonessential amino acids and, as mentioned earlier, detoxify ammonia (produced when amino acids are oxidized for energy) by converting it to urea.

Nutrients not needed by the liver cells, as well as the products of liver metabolism, are released into the blood and drain from the liver in the hepatic vein to enter the systemic circulation, where they become available to other body cells.

Cholesterol Metabolism and Transport

Although it's a very important lipid in the diet, **cholesterol** is not used as an energy fuel. Instead, it serves as the structural basis of steroid hormones and vitamin D, and is a major building block of plasma membranes. Because we hear so much about "cutting down our cholesterol intake" in the media, it is always surprising to learn that only about 15 percent of blood cholesterol comes from the diet. The other 85 percent or so is made by the liver. Cholesterol is lost from the body when it is broken down and secreted in bile salts, which eventually leave the body in feces.

Because of the important role they play in fat and cholesterol transport, the lipoproteins, one class of proteins made by the liver and known by the buzzwords *HDLs* and *LDLs,* deserve a bit more attention.

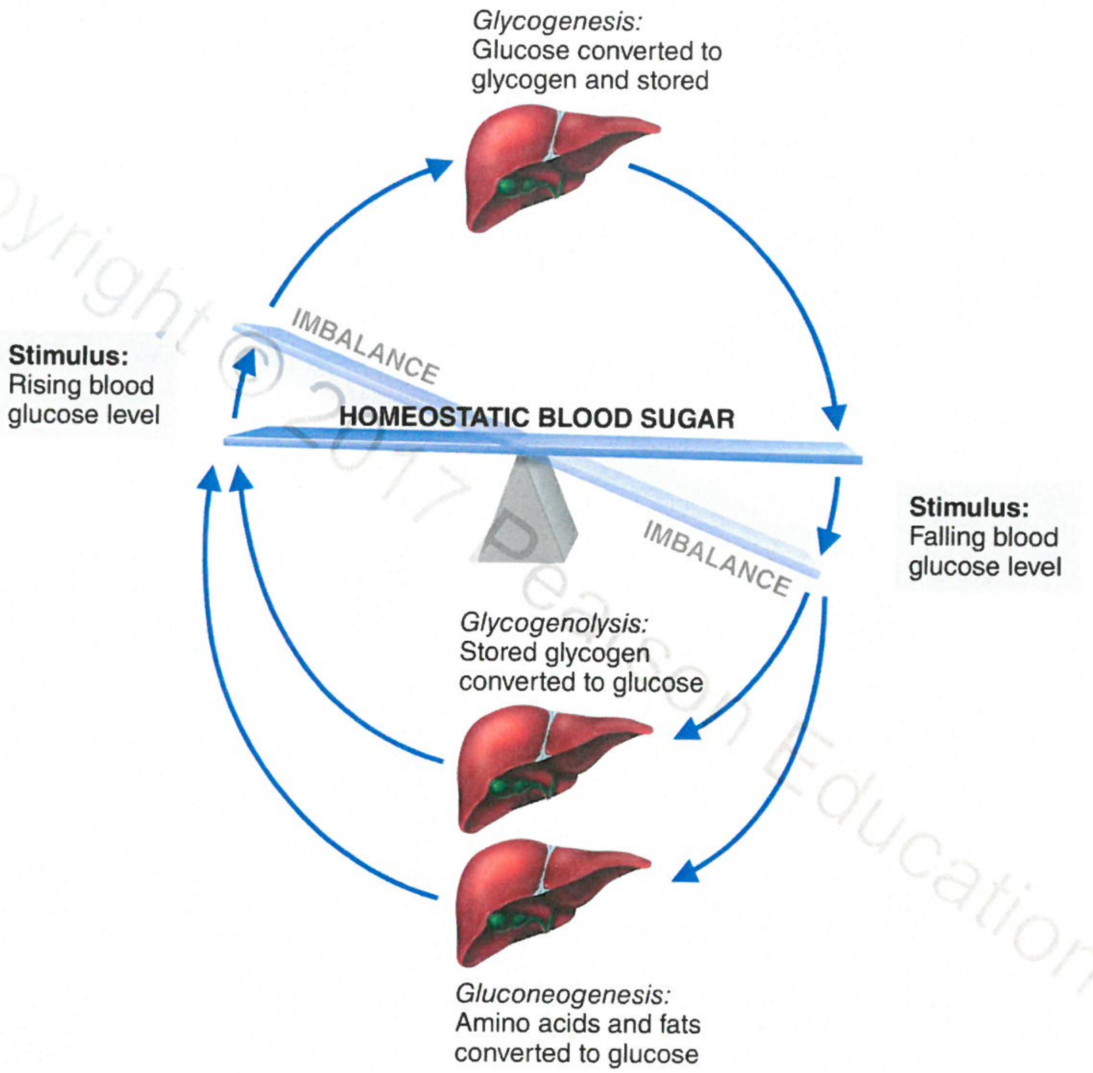

Figure 14.23 Metabolic events occurring in the liver as blood glucose levels rise and fall. When the blood glucose level is rising, the liver removes glucose from the blood and stores it as glycogen (glycogenesis). When the blood glucose level falls, the liver breaks down stored glycogen (glycogenolysis) and makes new glucose from amino acids and fats (gluconeogenesis). The glucose is then released to the blood to restore homeostasis of blood sugar.

Fatty acids, fats, and cholesterol are insoluble in water, so they cannot circulate freely in the bloodstream. Instead they are transported bound to the small lipid-protein complexes called lipoproteins. Although the entire story is complex, the important thing to know is that the **low-density lipoproteins,** or **LDLs,** transport cholesterol and other lipids *to* body cells, where they are used in various ways. If large amounts of LDLs are circulating, the chance that fatty substances will be deposited on the arterial walls, initiating atherosclerosis, is high. Because of this possibility, the LDLs are unkindly tagged as "bad lipoproteins." By contrast, the lipoproteins that transport cholesterol *from* the tissue cells (or arteries) to the liver for disposal in bile are **high-density lipoproteins,** or **HDLs.** High HDL levels are considered "good" because the cholesterol is destined to be broken down and eliminated from the body. Obviously both LDLs and HDLs are "good and necessary"; it is just their relative ratio in the blood that determines whether or not potentially lethal cholesterol deposits are likely to be laid down in the artery walls. In general, aerobic exercise, a diet low in saturated fats and cholesterol, and abstaining from smoking and drinking coffee all appear to favor a desirable HDL/LDL ratio.

Did You Get It?

29. *What is gluconeogenesis?*

30. *If you had your choice, would you prefer to have high blood levels of HDLs or LDLs? Explain your answer.*

(For answers, see Appendix D.)

Body Energy Balance

14-19 Explain the importance of energy balance in the body, and indicate consequences of energy imbalance.

When any fuel is burned, it consumes oxygen and liberates heat. The "burning" of food fuels by body cells is no exception. Energy cannot be created or destroyed—it can only be converted from one form to another (see Chapter 2). If we apply this principle to cellular metabolism, it means that a dynamic balance exists between the body's energy intake and its energy output:

Energy intake = total energy output
(heat + work + energy storage)

Energy intake is the energy liberated during food oxidation—that is, during the reactions of glycolysis, the Krebs cycle, and the electron transport chain. **Energy output** includes the energy we immediately lose as heat (about 60 percent of the total), plus that used to do work (driven by ATP), plus energy that is stored in the form of fat or glycogen. Energy storage is important only during periods of growth and during net fat deposit.

Regulation of Food Intake

When energy intake and energy output are balanced, body weight remains stable. When they are not, we either gain or lose weight. Because body weight in most people is surprisingly stable, mechanisms that control food intake or heat production or both must exist. Unhappily for many people, the body's weight-controlling systems appear to be designed more to protect us against weight loss than weight gain. (Some weight-control methods used by people who are obese are discussed in "A Closer Look" on pp. 503–504.)

But how is food intake controlled? That is a difficult question, and one that is still not fully answered. For example, what type of receptor could sense the body's total calorie content and alert one to start eating or to put down that fork? Despite heroic research efforts, no such single receptor type has been found.

It has been known for some time that the hypothalamus releases several peptides that influence feeding behavior. Current theories of how feeding behavior and hunger are regulated focus most importantly on neural signals from the digestive tract, bloodborne signals related to body energy stores, and hormones. To a smaller degree, body temperature and psychological factors also seem to play a role. All these factors appear to operate through feedback signals to the feeding centers of the brain. Brain receptors include thermoreceptors, chemoreceptors (for glucose, insulin, and others), and receptors that respond to leptin and other peptides. Sensors in peripheral locations have also been suggested, with the liver and gut itself (alimentary canal) the prime candidates.

Metabolic Rate and Body Heat Production

14-20 List several factors that influence metabolic rate, and indicate each one's effect.

When nutrients are broken down to produce cellular energy (ATP), they yield different amounts of energy. As mentioned earlier, the energy value of foods is measured in a unit called the *kilocalorie (kcal)*. In general, carbohydrates and proteins each yield 4 kcal/gram, and fats yield 9 kcal/gram when they are broken down for energy production. Most meals, and even many individual foods, are mixtures of carbohydrates, fats, and proteins. To determine the caloric value of a meal, we must know how many grams of each type of foodstuff it contains. For most of us, this is a difficult chore indeed, but approximations can easily be made with the help of a simple, calorie-values guide available in most drugstores.

Basal Metabolic Rate The amount of energy used by the body is also measured in kilocalories. The **basal metabolic rate (BMR)** is the amount of heat produced by the body per unit of time when it is under basal conditions—that is, at rest. It reflects the energy supply a person's body needs just to perform essential life activities such as breathing, maintaining the heartbeat, and kidney function. An average 70-kg (154-pound) adult has a BMR of about 60 to 72 kcal/hour.

Table 14.3 Factors Determining the Basal Metabolic Rate (BMR)

Factor	Variation	Effect on BMR
Surface area	Large surface area in relation to body volume, as in thin, small individuals	Increased
	Small surface area in relation to body volume, as in large, heavy individuals	Decreased
Sex	Male Female	Increased Decreased
Thyroxine production	Increased Decreased	Increased Decreased
Age	Young, rapid growth Aging, elderly	Increased Decreased
Strong emotions (anger or fear) and infections		Increased

Many factors influence BMR, including surface area and gender. For example, small, thin males tend to have a higher BMR than large, obese females (Table 14.3). Age is also important; children and adolescents require large amounts of energy for growth and have relatively high BMRs. In old age, the BMR decreases dramatically as the muscles begin to atrophy.

The amount of **thyroxine** produced by the thyroid gland is probably the most important factor in determining a person's BMR; hence, thyroxine has been dubbed the "metabolic hormone." The more thyroxine produced, the higher the oxygen consumption and ATP use, and the higher the metabolic rate. In the past, most BMR tests were done to determine whether sufficient thyroxine was being made. Today, thyroid activity is more easily assessed by blood tests.

Homeostatic Imbalance 14.11

Hyperthyroidism causes a host of effects due to the excessive metabolic rate it produces. The body catabolizes stored fats and tissue proteins, and despite increased hunger and food intake, the person often loses weight. Bones weaken and body muscles, including the heart, atrophy. In contrast, **hypothyroidism** results in slowed metabolism, obesity, and diminished thought processes.

Total Metabolic Rate When we are active, the body must oxidize more glucose to provide energy for the additional activities. Digesting food and even modest physical activity increase the body's caloric requirements dramatically. These additional fuel requirements are above and beyond the energy required to maintain the body in the basal state. **Total metabolic rate (TMR)** refers to the total amount of kilocalories the body must consume to fuel all ongoing activities. Muscular work is the major body activity that increases the TMR. Even slight increases in skeletal muscle activity cause remarkable leaps in metabolic rate. When a well-trained athlete exercises vigorously for several minutes, the TMR may increase to 15 to 20 times normal, and it remains elevated for several hours afterward.

When the total number of kilocalories consumed is equal to the TMR, homeostasis is maintained, and our weight remains constant. However, if we eat more than we need to sustain our activities, excess kilocalories appear in the form of fat deposits. Conversely, if we are extremely active and do not properly feed the "metabolic furnace," we begin to break down fat reserves and even tissue proteins to satisfy our TMR. This principle is used in every good weight-loss diet. (The total kilocalories needed are calculated on the basis of body size and age. Then, 20 percent or more of the requirements are cut from the daily diet.) If the dieting person exercises regularly, weight drops off even more quickly because the TMR increases above the person's former rate.

Did You Get It?

31. *Which of the following would you expect to yield a relatively high BMR: old age, large surface area relative to body volume, female sex, deficient thyroxine production?*

(For the answer, see Appendix D.)

Body Temperature Regulation

14-21 Describe how body temperature is regulated.

Although we have been emphasizing that foods are "burned" to produce ATP, remember that ATP is not the only product of cell catabolism. Most of the energy released as foods are oxidized escapes as heat. Less than 40 percent of available food energy is actually captured to form ATP. The heat released warms the tissues and, more important, the blood, which circulates to all body tissues, keeping them at homeostatic temperatures, which allows metabolism to occur efficiently.

Body temperature reflects the balance between heat production and heat loss. The body's thermostat is in the *hypothalamus* of the brain. Through autonomic nervous system pathways, the hypothalamus continuously regulates body temperature around a set point of 35.6° to 37.8°C (96° to 100°F) by initiating heat-loss or heat-promoting mechanisms (Figure 14.24, p. 500).

Heat-Promoting Mechanisms When the environmental temperature is low, the body must produce more heat to maintain normal body temperature (37°C). And if, for whatever reason, the temperature of circulating blood falls, body heat must be conserved and more heat generated to restore normal body (blood) temperature. Short-term means of accomplishing this are **vasoconstriction** of blood vessels of the skin and **shivering.**

When the skin vasculature constricts, the skin is temporarily bypassed by the blood, and blood is rerouted to the deeper, more vital body organs. When this happens, the temperature of the exposed skin drops to that of the external environment.

Homeostatic Imbalance 14.12

Restriction of blood delivery to the skin is no problem for brief periods of time. But if it is extended, the skin cells, chilled by internal ice crystals and deprived of oxygen and nutrients, begin to die. This condition, called **frostbite,** is extremely serious.

When the *core* body temperature (the temperature of the deep organs) drops to the point beyond which simple constriction of skin capillaries can handle the situation, shivering begins. Shivering, involuntary shudderlike contractions of the voluntary muscles, is very effective in increasing the body temperature because skeletal muscle activity produces large amounts of heat.

Homeostatic Imbalance 14.13

Extremely low body temperature resulting from prolonged exposure to cold is **hypothermia.** In hypothermia, the individual's vital signs (respiratory rate, blood pressure, heart rate) decrease. The person becomes drowsy and oddly comfortable, even though previously he or she felt extremely cold. Uncorrected, the situation progresses to coma and finally death as metabolic processes grind to a stop.

Heat-Loss Mechanisms Just as the body must be protected from becoming too cold, it must also be protected from excessively high temperatures. Most heat loss occurs through the skin via **radiation** or **evaporation.** When body temperature increases above what is desirable, the blood vessels serving the skin dilate and capillary beds in the skin become flushed with warm blood. As a result, heat radiates from the skin surface. However, if the external environment is as hot as or hotter than the body, heat cannot be lost by radiation. In such cases, the only means of getting rid of excess heat is by the evaporation of perspiration off the skin surface. This is an efficient means of body-heat loss as long as the air is dry. If it is humid, evaporation occurs at a much slower rate. Our heat-liberating mechanisms don't work well, and we feel miserable and irritable.

Homeostatic Imbalance 14.14

When normal heat loss processes become ineffective, the resulting **hyperthermia,** or elevated body temperature, depresses the hypothalamus. As a result, a vicious positive feedback cycle occurs: Soaring body temperature increases the metabolic rate, which in turn increases heat production. The skin becomes hot and dry; and, as the temperature

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