CHAPTER 5

Digestion, Absorption, and Metabolism

KEY CONCEPTS

- Through a balanced system of mechanical and chemical digestion, food is broken down into smaller substances, and the nutrients are then released for biologic use.
- Special organ structures and functions accomplish these tasks through the successive parts of the overall system.
- Absorption, transport, and metabolism allow for the distribution, use, and storage of nutrients throughout the body.

As described in previous chapters, nutrients that the body requires do not come ready to use; rather, they are packaged as foods in a variety of forms. Therefore, whole food must be broken down into smaller substances for absorption and metabolism to meet the body's needs. Digestion of the macronutrients—carbohydrates, fat, and protein—has been discussed in preceding chapters.

This chapter views the overall process of food digestion and nutrient absorption as one continuous whole that involves a series of successive events. In addition, metabolism and the unique body structures and functions that make this process—as well as life—possible are reviewed.

DIGESTION

Basic Principles

Principle of Change

Body cells cannot use food as it is eaten. Food must be changed into simpler substances for absorption and then into even more simple substances that cells can use to sustain life. Preparing food for the body's use involves many steps, including **digestion**, **absorption**, **transport**, and **metabolism**.

digestion the process by which food is broken down in the gastrointestinal tract to release nutrients in forms that the body can absorb.

absorption the process by which nutrients are taken into the cells that line the gastrointestinal tract.

transport the movement of nutrients through the circulatory system from one area of the body to another.

metabolism the sum of the vast number of chemical changes in the cell that ultimately produce the materials that are essential for energy, tissue building, and metabolic controls.

Principle of Wholeness

The different parts of the gastrointestinal (GI) tract and accessory organs are shown in Figure 5-1. The individual parts of the GI system works systematically together as a

Multiple Choice

1. Nine of the 20 amino acids are indispensable, which means that
   a. the body cannot make them and must obtain them from the diet.
   b. they are required for body processes and the rest are not.
   c. the body makes them because they are essential to life.
   d. after making them, the body uses them for growth.
2. A complete protein food of high biologic value contains
   a. all 20 of the amino acids in sufficient amounts to meet human requirements.
   b. the nine indispensable amino acids in any proportion, because the body can always fill in the remaining differences.
   c. all of the 20 amino acids from which the body can make additional amounts of the nine indispensable ones as necessary.
   d. all nine of the indispensable amino acids in correct proportion to meet human requirements.
3. A state of negative nitrogen balance may occur during periods of
   a. pregnancy.
   b. adolescence.
   c. injury or surgery.
   d. infancy.

Evolve Please refer to the Students' Resource section of this text's Evolve Web site for additional study resources.

REFERENCES

1. Food and Nutrition Board, Institute of Medicine. *Dietary reference intakes for energy, carbohydrate, fiber, fat, fatty acids, cholesterol, protein, and amino acids*. Washington, DC: National Academies Press; 2002.
2. Stahler C. How many adults are vegetarian? *Veg J*. 2006;25:14-15.
3. Craig WJ, Mangels AR. Position of the American dietetic association: vegetarian diets *J Am Diet Assoc*. 2009; 109(7):1266-1282.
4. Fraser GE. Vegetarian diets: what do we know of their effects on common chronic diseases? *Am J Clin Nutr*. 2009;89(5):1607S-1612S.
5. Barnard ND, Katcher HI, Jenkins DJ, et al. Vegetarian and vegan diets in type 2 diabetes management. *Nutr Rev*. 2009;67(5):255-263.
6. Segasothy M, Phillips PA. Vegetarian diet: panacea for modern lifestyle diseases? *QJM*. 1999;92(9):531-544.
7. Craig WJ. Health effects of vegan diets. *Am J Clin Nutr*. 2009;89(5):1627S-1633S.
8. Millward DJ, Layman DK, Tomé D, Schaafsma G. Protein quality assessment: impact of expanding understanding of protein and amino acid needs for optimal health. *Am J Clin Nutr*. 2008;87(5):1576S-1581S.
9. Ahmed T, Rahman S, Cravioto A. Oedematous malnutrition. *Indian J Med Res*. 2009;130(5):651-654.
10. U.S. Department of Agriculture, Agricultural Research Service. *What we eat in America* (website): www.ars.usda.gov/Services/docs.htm?docid=13793. Accessed September 22, 2011.
11. U.S. Department of Agriculture, U.S. Department of Health and Human Services. *Dietary guidelines for Americans, 2010*. Washington, DC: U.S. Government Printing Office; 2010.
12. U.S. Department of Agriculture, Center for Nutrition Policy and Promotion. *USDA's myplate home page* (website): www.choosemyplate.gov. Accessed August 23, 2011.

FURTHER READING AND RESOURCES

The following organizations are good sources of information about vegetarian diets.

Food and Nutrition Information Center. http://fnic.nal.usda.gov

Medline Plus (key search word: "vegetarianism"). www.nlm.nih.gov/medlineplus/vegetariandiet.html

North American Vegetarian Society. www.navs-online.org

Vegetarian Nutrition Dietetic Practice Group. www.vegetariannutrition.net

The Vegetarian Resource Group. www.vrg.org

Fuhrman J, Ferreri DM. Fueling the vegetarian (vegan) athlete. *Curr Sports Med Rep*. 2010;9(4):233-241.

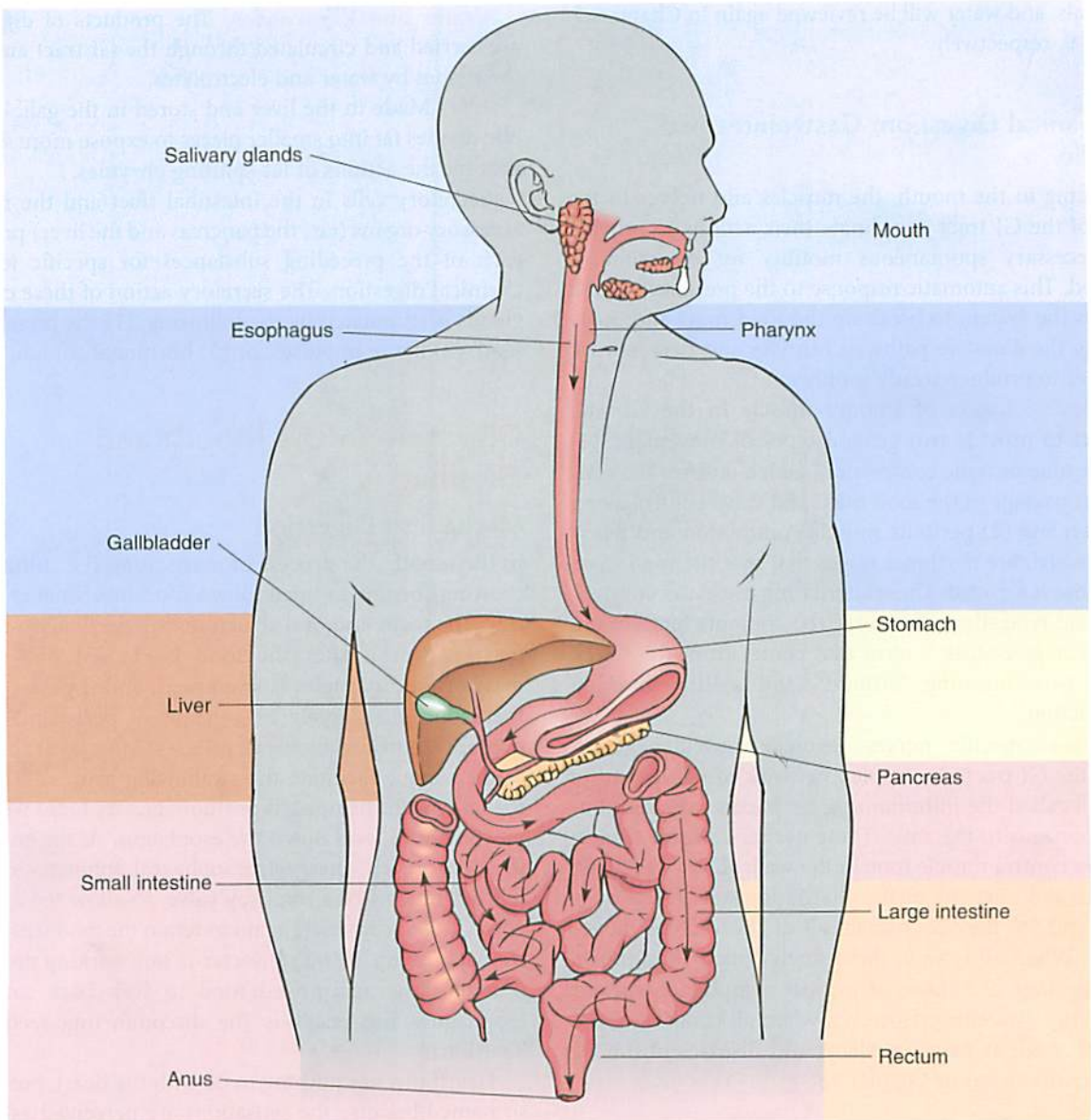

Figure 5-1 The gastrointestinal system. Through the successive parts of the system, multiple activities of digestion liberate food nutrients for use. (Courtesy Rolin Graphics.)

whole to complete the process of digestion and metabolism. Food components travel through this system until they ultimately are absorbed and delivered to the cells or excreted as waste.

Mechanical and Chemical Digestion

For nutrients to be absorbed, food must go through a series of mechanical and chemical changes. Together, these two actions encompass the overall process of digestion.

The specific mechanical and chemical actions that occur during the digestion of the macronutrients (i.e., carbohydrates, proteins, and fats) have previously been discussed. Of the micronutrients, most vitamins and minerals require little to no digestion. There are some exceptions (e.g., vitamins A and B_{12}, biotin) that require digestion before absorption can take place. Water does not require digestion, and it is easily absorbed into the general circulation. This chapter touches on those actions as a whole and as an interdependent process. Vitamins,

minerals, and water will be reviewed again in Chapters 7, 8, and 9, respectively.

Mechanical Digestion: Gastrointestinal Motility

Beginning in the mouth, the muscles and nerves in the walls of the GI tract coordinate their actions to provide the necessary spontaneous motility for digestion to proceed. This automatic response to the presence of food enables the system to break up the food mass and move it along the digestive pathway. Muscles and nerves work together to produce steady motility.

Muscles. Layers of smooth muscle in the GI wall interact to provide two general types of movement: (1) muscle tone or tonic contraction, which ensures the continuous passage of the food mass and valve control along the way; and (2) periodic muscle contraction and relaxation, which are rhythmic waves that mix the food mass and move it forward. These alternating muscular contractions and relaxations that force the contents forward are known as *peristalsis*, a term that comes from the Greek words *peri*, meaning "around," and *stalsis*, meaning "contraction."

Nerves. Specific nerves regulate muscular action along the GI tract. A complex network of nerves in the GI wall called the *intramural nerve plexus* extends from the esophagus to the anus. These nerves do three things: (1) they control muscle tone in the wall; (2) they regulate the rate and intensity of the alternating muscle contractions; and (3) they coordinate all of the various movements. When all is well, these finely tuned movements flow together like those of a great symphony, without conscience awareness. However, when all is not well, the discord is felt as pain. Problems and diseases of the GI tract are discussed in Chapter 18.

Chemical Digestion: Gastrointestinal Secretions

A number of secretions work together to make chemical digestion possible. Five types of substances generally are involved.

Hydrochloric Acid and Buffer Ions. Hydrochloric acid and buffer ions are needed to produce the correct pH (i.e., the degree of acidity or alkalinity) that is necessary for enzymatic activity.

Enzymes. Digestive enzymes are proteins of a specific kind and quantity for breaking down nutrients.

Mucus. Secretions of mucus lubricate and protect the mucosal tissues that line the GI tract, and they help to mix the food mass.

Water and Electrolytes. The products of digestion are carried and circulated through the GI tract and into the tissues by water and electrolytes.

Bile. Made in the liver and stored in the gallbladder, bile divides fat into smaller pieces to expose more surface area for the actions of fat-splitting enzymes.

Secretory cells in the intestinal tract and the nearby accessory organs (i.e., the pancreas and the liver) produce each of the preceding substances for specific jobs in chemical digestion. The secretory action of these cells or glands is stimulated by the following: (1) the presence of food; (2) nerve impulses; or (3) hormonal stimuli.

Digestion in the Mouth and Esophagus

Mechanical Digestion

In the mouth, the process of mastication (i.e., biting and chewing) begins to break down food into smaller particles. The teeth and oral structures are particularly suited for this work. After the food is chewed, the mixed mass of food particles is swallowed, and it passes down the esophagus, largely as a result of peristaltic waves that are controlled by nerve reflexes. Muscles at the base of the tongue facilitate the swallowing process. Then, if the body is in the upright position, gravity helps with the movement of food down the esophagus. At the entrance to the stomach, the gastroesophageal sphincter muscle relaxes, much like a one-way valve, to allow the food to enter; it then constricts again to retain the food within the stomach cavity. If the sphincter is not working properly, it may allow acid-mixed food to seep back into the esophagus. The result is the discomforting feeling of heartburn.

Heartburn has nothing to do with the heart, but it was so named because the sensations are perceived as originating in the region of the heart. A hiatal hernia is another common cause of heartburn; this occurs when part of the stomach protrudes upward into the chest cavity (i.e., the thorax; see Chapter 18).

Chemical Digestion

The salivary glands secrete material that contains **salivary amylase**, which is also called *ptyalin*. *Amylase* is the general name for any starch-splitting enzyme. Small

salivary amylase a starch-splitting enzyme in the mouth that is secreted by the salivary glands and that is commonly called *ptyalin* (from the Greek word *ptyalon*, meaning "spittle").

glands at the back of the tongue (i.e., von Ebner's glands) secrete lingual lipase. *Lipase* is the general name for any fat-splitting enzyme. However, in this case, food does not remain in the mouth long enough for much chemical action to occur. During infancy, lingual lipase is a more relevant enzyme for the digestion of milk fat. The salivary glands also secrete a mucous material that lubricates and binds food particles to facilitate the swallowing of each food bolus (i.e., lump of food material). Mucous glands also line the esophagus, and their secretions help to move the food mass toward the stomach.

Digestion in the Stomach

Mechanical Digestion

Under sphincter-muscle control from the esophagus, which joins the stomach at the cardiac notch, the food enters the fundus (i.e., the upper portion of the stomach) in individual bolus lumps. Within the stomach, muscles gradually knead, store, mix, and propel the food mass forward in slow, controlled movements. By the time the food mass reaches the antrum (i.e., the lower portion of the stomach), it is now a semiliquid, acid–food mix called ***chyme***. A constricting sphincter muscle at the end of the stomach called the *pyloric valve* controls the flow at this point. This valve slowly releases acidic chyme so that it can be quickly buffered by the alkaline intestinal secretions and not irritate the mucosal lining of the duodenum, which is the first section of the small intestine. The caloric density of a meal, which mainly results from its fat composition, influences the rate of stomach emptying at the pyloric valve. The major parts of the stomach are shown in Figure 5-2.

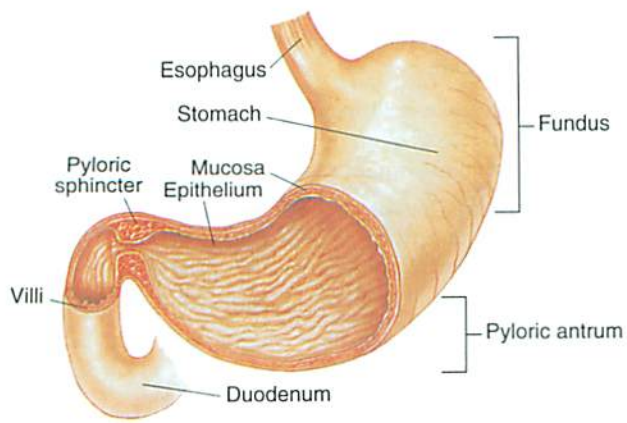

Figure 5-2 Stomach. (Reprinted from Raven PH, Johnson GB. *Biology*, 3rd ed. New York: McGraw-Hill; 1992.)

Chemical Digestion

The gastric secretions contain three types of materials that help with chemical digestion in the stomach.

Acid. The hormone **gastrin** stimulates parietal cells within the lining of the stomach to secrete hydrochloric acid. Hydrochloric acid creates the necessary degree of acidity for gastric enzymes to work, and it also activates the first protease, pepsinogen, in the stomach.

Mucus. Mucous secretions protect the stomach lining from the erosive effect of hydrochloric acid. Secretions also bind and mix the food mass and help to move it along.

Enzymes. The inactive enzyme pepsinogen is secreted by stomach cells, and it is activated by hydrochloric acid to become the protein-splitting enzyme **pepsin.** Other cells produce small amounts of a specific gastric lipase called *tributyrinase,* which works on tributyrin (i.e., butterfat); however, this is a relatively minor activity in the stomach.

Various sensations, emotions, and foods stimulate the nerve impulses that trigger these secretions. The concept that the stomach is said to "mirror the person within" is not without merit. For example, anger and hostility increase secretions, whereas fear and depression decrease secretions and inhibit blood flow and motility. Additional hormonal stimulus occurs in response to food entering the stomach.

Digestion in the Small Intestine

Up to this point, the digestion of food has largely been mechanical, and it has resulted in the delivery of a semifluid mixture of fine food particles and watery secretions to the small intestine. Chemical digestion has been minimal. Thus, the major task of digestion and the absorption that follows occurs in the small intestine. The structural parts, synchronized movements, and array of specific enzymes of the small intestine are highly developed for the final step of mechanical and chemical digestion.

chyme the semifluid food mass in the gastrointestinal tract that is present after gastric digestion.

gastrin a hormone that helps with gastric motility, that stimulates the secretion of gastric acid by the parietal cells of the stomach, and that stimulates the chief cells to secrete pepsinogen.

pepsin the main gastric enzyme specific to proteins; it begins breaking large protein molecules into shorter-chain polypeptides; gastric hydrochloric acid is necessary for its activation.

Mechanical Digestion

Under the control of nerve impulses, the muscular walls of the small intestines stretch from the food mass or hormonal stimuli, and the intestinal muscles produce several types of movement that aid digestion, as follows:

- *Peristaltic waves* slowly push the food mass forward, sometimes with long, sweeping waves over the entire length of the intestine.
- *Pendular movements* from small, local muscles sweep back and forth, thereby stirring the chyme at the mucosal surface.
- *Segmentation rings* from the alternating contraction and relaxation of circular muscles progressively chop the food mass into successive soft lumps and then mix them with secretions.
- *Longitudinal rotation* by long muscles that run the length of the intestine rolls the slowly moving food mass in a spiral motion to mix it and expose new surfaces for absorption.
- *Surface villi motions* stir and mix the chyme at the intestinal wall, thereby exposing additional nutrients for absorption.

Chemical Digestion

The small intestines, together with the GI accessory organs (i.e., the pancreas, liver, and gallbladder), supply many secretory materials to accomplish the major chore of chemical digestion. The pancreas and intestines secrete enzymes that are specific for the digestion of each macronutrient.

Pancreatic Enzymes

1. *Carbohydrate:* **Pancreatic amylase** converts starch into the disaccharides maltose, and sucrose.
2. *Protein:* **Trypsin** and **chymotrypsin** split large protein molecules into smaller and smaller peptide fragments and finally into single amino acids. **Carboxypeptidase** removes end amino acids from peptide chains.
3. *Fat:* **Pancreatic lipase** converts fat into glycerides and fatty acids.

Intestinal Enzymes

1. *Carbohydrate:* Disaccharidases (i.e., maltase, lactase, and sucrase) convert their respective disaccharides (i.e., maltose, lactose, and sucrose) into monosaccharides (i.e., glucose, galactose, and fructose).
2. *Protein:* The intestinal enzyme enterokinase activates trypsinogen, which is released from the pancreas to become the protein-splitting enzyme trypsin. Amino peptidase removes end amino acids from polypeptides. Dipeptidase splits dipeptides into their two remaining amino acids.
3. *Fat:* Intestinal lipase splits fat into glycerides and fatty acids.

Mucus. Large quantities of mucus, which are secreted by intestinal glands, protect the mucosal lining from the irritation and erosion caused by the highly acidic gastric contents that enter the duodenum.

Bile. Bile is an emulsifying agent and an important part of fat digestion and absorption. It is produced by the liver and stored in the adjacent gallbladder, and it is ready for use when fat enters the intestine.

Hormones. The hormone secretin, which is produced by the mucosal glands in the first part of the intestine, controls the acidity and secretion of enzymes from the pancreas. The resulting alkaline environment in the small intestine, with a pH greater than 8, is necessary for the activity of the pancreatic enzymes. The hormone cholecystokinin, which is secreted by intestinal mucosal glands when fat is present, triggers the release of bile from the gallbladder to emulsify fat.

The arrangement of accessory organs to the duodenum, which is the first section of the small intestine, is shown in Figure 5-3. These organs make up the biliary system. The liver is sometimes called the "metabolic capital" of the body, because it performs numerous functions for the metabolism of all converging nutrients (Box 5-1). The liver's many metabolic functions are reviewed in greater detail in Chapter 18.

The various nerve and hormone controls of digestion are illustrated in Figure 5-4. Although small individual summaries of digestion are given in each of the macronutrient chapters, a general summary of the entire digestive process is shown in Figure 5-5 so that the overall process can be viewed as it is: one continuous and integrated whole.

pancreatic amylase a major starch-splitting enzyme that is secreted by the pancreas and that acts in the small intestine.

trypsin a protein-splitting enzyme produced in the pancreas and released into the small intestine; the inactive precursor trypsinogen is activated by enterokinase.

chymotrypsin one of the protein-splitting and milk-curdling pancreatic enzymes that is activated in the small intestine from the precursor chymotrypsinogen; it breaks specific amino acid peptide links of protein.

carboxypeptidase a protein enzyme that splits off the carboxyl group (i.e., –COOH) at the end of peptide chains.

pancreatic lipase a major fat-splitting enzyme produced by the pancreas and secreted into the small intestine to digest fat.

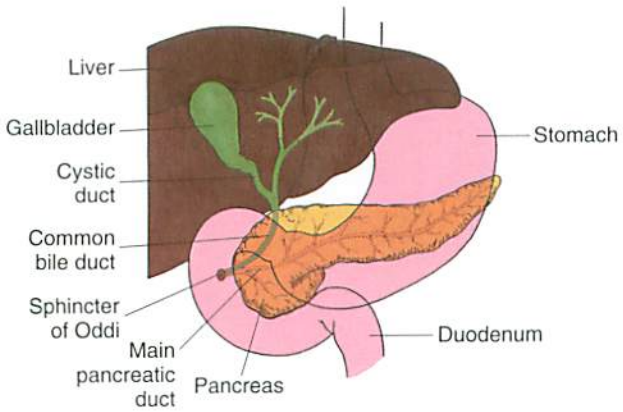

Figure 5-3 Organs of the biliary system and the pancreatic ducts.

ABSORPTION AND TRANSPORT

When digestion is complete, food has been changed into simple end products that are ready for cell use. Carbohydrate foods are reduced to the simple sugars glucose, fructose, and galactose, and fats are transformed into fatty acids and glycerides. Protein foods are changed into single amino acids, and vitamins and minerals are also liberated. With a water base for solution and transport in addition to the necessary electrolytes, the whole fluid food-derived mass is now prepared for absorption. For many nutrients, especially certain vitamins and minerals, the point of absorption becomes the vital gatekeeper that determines how much of a given nutrient is kept for body use. Although the GI tract is quite efficient, 100% of all

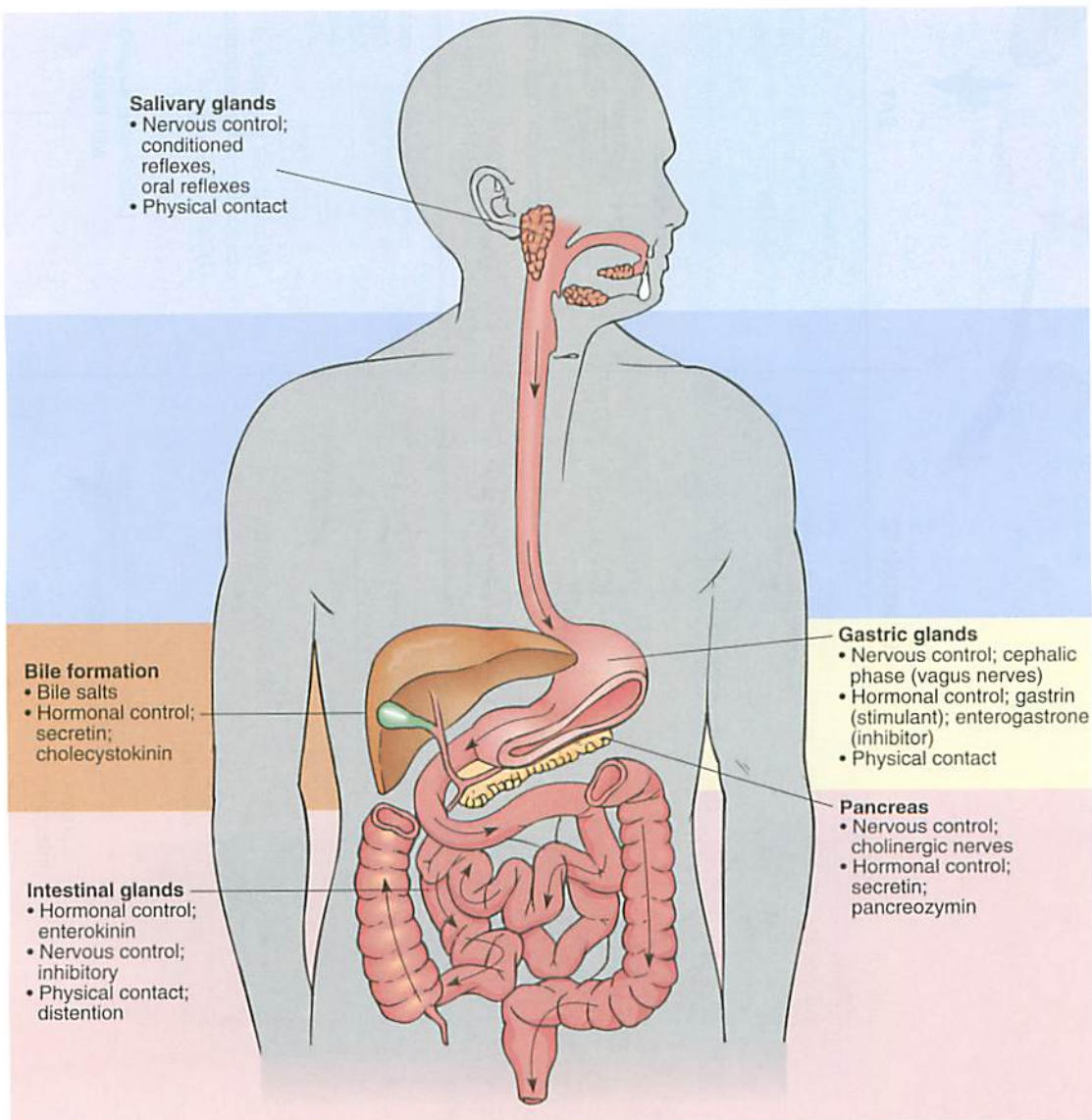

Figure 5-4 Summary of the factors that influence secretions in the gastrointestinal tract. (Courtesy Rolin Graphics.)

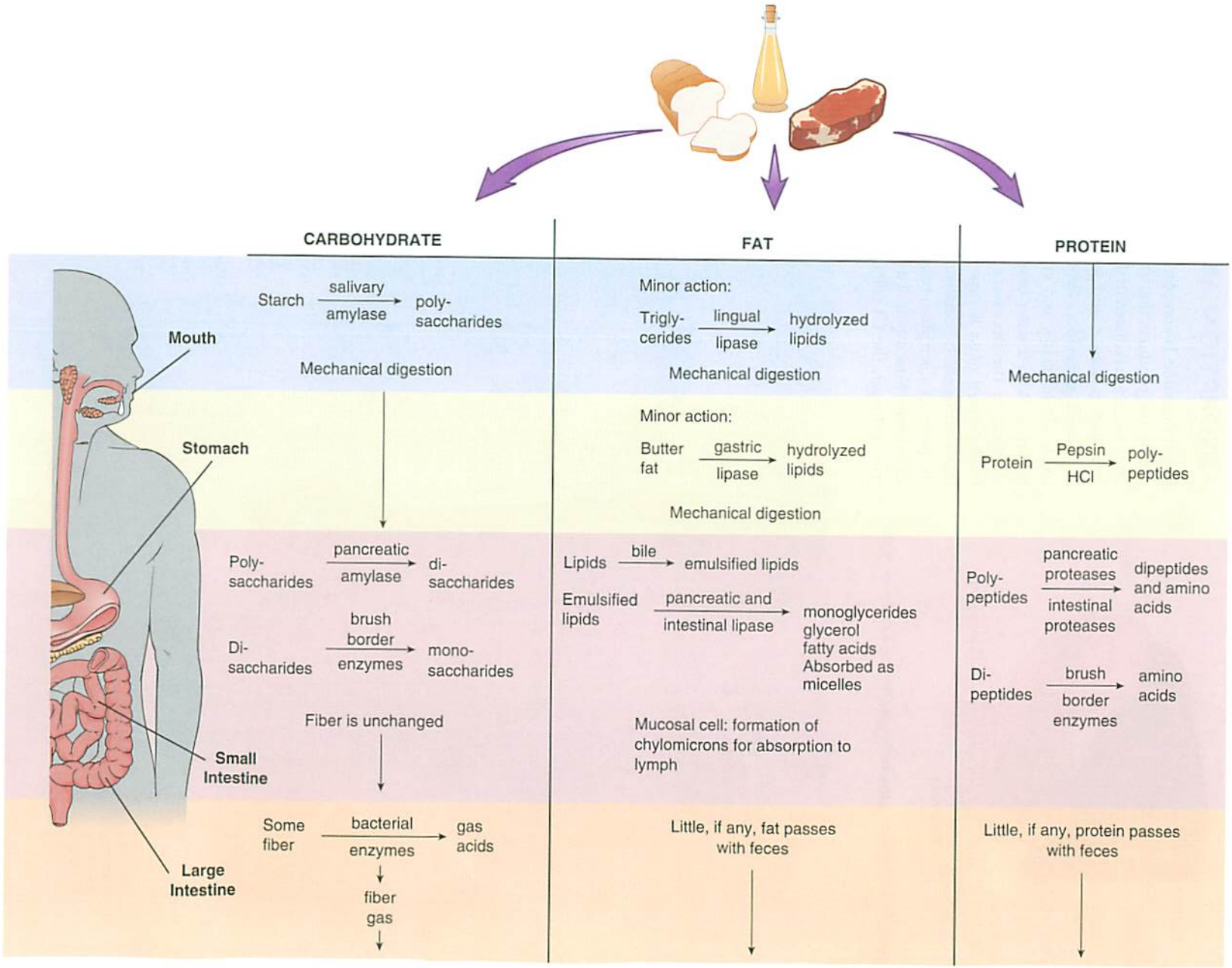

Figure 5-5 Summary of the digestive processes. (Courtesy Rolin Graphics.)

BOX 5-1 FUNCTIONS OF THE LIVER

Major Functions
- Bile production
- Synthesis of proteins and blood-clotting factors
- Metabolism of hormones and medications
- Regulation of blood glucose levels
- Urea production to remove the waste products of normal metabolism

Specific Metabolic Functions of the Macronutrients
- Lipolysis: breaking down lipids into fatty acids and glycerol
- Lipogenesis: building up lipids from fatty acids and glycerol
- Glycolysis: breaking down glucose into pyruvate to enter the Krebs cycle
- Gluconeogenesis: converting noncarbohydrate substances into glucose
- Glycogenolysis: breaking down glycogen into individual glucose units
- Glycogenesis: combining units of glucose to store as glycogen
- Protein degradation: breaking down proteins into single amino acids
- Protein synthesis: building complete proteins from individual amino acids

nutrients consumed is not absorbed as a result of varying degrees of bioavailability. A nutrient's bioavailability depends on the following: (1) the amount of nutrient present in the GI tract; (2) competition among nutrients for common absorptive sites; and (3) the form in which the nutrient is present. This degree of bioavailability is a factor in setting dietary intake standards for all macronutrients and micronutrients.[1-6]

Absorption in the Small Intestine

Absorbing Structures

Three important structures of the intestinal wall surface (Figure 5-6) are particularly adapted to ensure the maximal absorption of essential nutrients in the digestive process:

- *Mucosal folds:* Like the hills and valleys of a mountain range, the surface of the small intestine piles into many folds. Mucosal folds can easily be seen when such tissue is examined.
- *Villi:* Closer examination under a regular light microscope reveals small, finger-like projections that cover the piled-up folds of the mucosal lining. These little villi further increase the area of exposed surface. Each villus has an ample supply of blood vessels to receive protein and carbohydrate materials as well as a lymph vessel to receive fat-soluble nutrients. This lymph vessel is called a *lacteal,* because the fatty chyme is creamy at this point and looks like milk.
- *Microvilli:* Even closer examination with an electron microscope reveals a covering of smaller projections on the surface of each tiny villus. The covering of microvilli on each villus is called the *brush border,* because it looks like bristles on a brush.

These three unique structures of the inner intestinal wall—folds, villi, and microvilli—combine to make the inner surface some 600 times greater than the area of the outer surface of the intestine. The length of the small intestine is approximately 660 cm (22 ft). This remarkable organ is well adapted to deliver nutrients into the circulation to the body's cells. If its entire surface were spread out on a flat plane, the total surface area is estimated to be as large as half of a basketball court. Far from being the lowly gut, the small intestine is one of the most highly developed, exquisitely fashioned, and specialized tissues in the body.

Absorption Processes

A number of absorbing processes complete the task of moving vital nutrients across the inner intestinal wall and into the body circulation (Figure 5-7). These processes include diffusion, energy-driven active transport, and pinocytosis:

- *Simple diffusion* is the force by which particles move outward in all directions from an area of greater concentration to an area of lesser concentration. Small materials that do not need the help of a specific protein channel to move across the mucosal cell wall use this method.
- *Facilitated diffusion* is similar to simple diffusion, but it makes use of a protein channel for the carrier-assisted movement of larger items across the mucosal cell membrane.

mucosal folds the large, visible folds of the mucous lining of the small intestine that increase the absorbing surface area.

villi small protrusions from the surface of a membrane; finger-like projections that cover the mucosal surfaces of the small intestine and that further increase the absorbing surface area; they are visible through a regular microscope.

microvilli extremely small, hair-like projections that cover all of the villi on the surface of the small intestine and that greatly extend the total absorbing surface area; they are visible through an electron microscope.

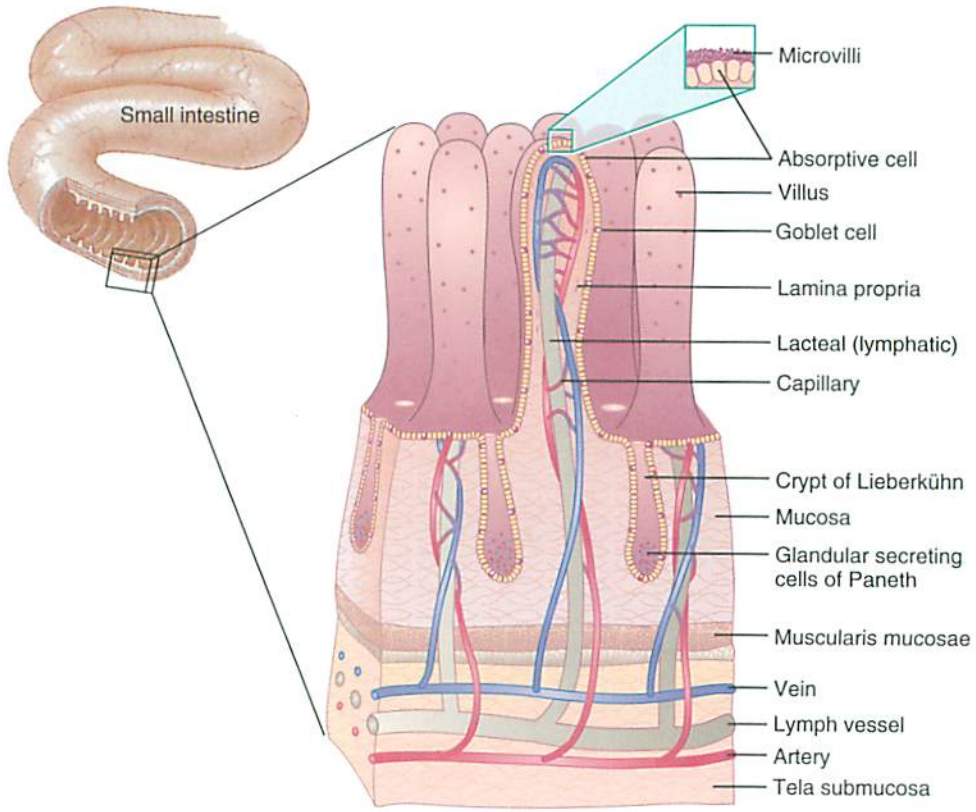

Figure 5-6 The intestinal wall. A diagram of the villi of the human intestine that shows its structure and the blood and lymph vessels. (Reprinted from Mahan LK, Escott-Stump S. *Krause's food & nutrition therapy.* 12th ed. Philadelphia: Saunders; 2008.)

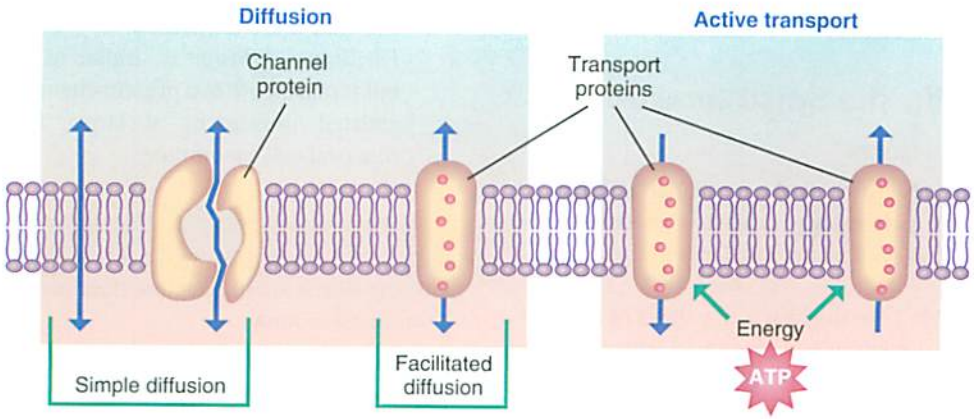

Figure 5-7 Transport pathways through the cell membrane. (Reprinted from Mahan LK, Escott-Stump S. *Krause's food & nutrition therapy.* 12th ed. Philadelphia: Saunders; 2008.)

- *Active transport* is the force by which particles move against their concentration gradient. Active transport mechanisms usually require some sort of carrier partner to help ferry the particles across the membrane. For example, glucose enters absorbing cells through an active transport mechanism that involves sodium as a partner.
- *Pinocytosis* is the penetration of larger materials by attaching to the thicker cell membrane and being engulfed by the cell.

Absorption in the Large Intestine

Water

The main absorptive task that remains for the large intestine is to absorb water. Most water in the chyme that enters the large intestine is absorbed in the first half of the colon. Only a small amount (approximately 100 mL) remains to form the feces and be eliminated.

Dietary Fiber

Food fiber is not digested, because humans lack the specific enzymes that are required to break the beta bonds between molecules. However, dietary fiber contributes important bulk to food mass and helps to form feces. The formation and passage of intestinal gas is a normal process of healthy digestion, but it can be problematic for some individuals (see the Clinical Applications box, "The Sometimes Embarrassing Effects of Digestion").

Macronutrients and Micronutrients

Table 5-1 summarizes the major features of intestinal nutrient absorption, including macronutrients and micronutrients. In addition, Figure 5-8 shows the location of absorption of each nutrient as well as the route through which it is absorbed (i.e., lymph or blood).

Transport

After being broken down from food and absorbed, nutrients must be transported to various cells throughout the body. This transportation requires the work of both the vascular and lymphatic systems (see Figure 5-6).

Vascular System

The vascular system is composed of veins and arteries, and it is responsible for supplying the entire body with nutrients, oxygen, and many other vital substances that are necessary for life via the blood. In addition, the vascular system transports waste (e.g., carbon dioxide, nitrogen) to the lungs and kidneys for removal.

Most of the products of digestion are water-soluble nutrients, which therefore can be absorbed into the vascular system (i.e., the blood circulatory system) directly from the intestinal cells. The nutrients travel first to the liver for immediate cell enzyme work before being dispersed to other cells throughout the body. The portion of circulation from the intestines to the liver is called the *portal circulation.*

Lymphatic System

Because fatty materials are not water soluble, another route must be provided. These fat molecules pass into the lymph vessels in the villi (e.g., the lacteals), flow into the larger lymph vessels of the body, and eventually enter the bloodstream through the thoracic duct.

Metabolism

At this point, the individual macronutrients in food have been broken down through digestion into the basic building blocks (i.e., monosaccharides, amino acids, and fatty acids) and absorbed into the bloodstream or the lymphatic system. Now these nutrients can be converted into needed energy or stored in the body for later use.

In addition, the micronutrients (i.e., vitamins and minerals) have been liberated from any bound proteins, and they are free for absorption. Once inside, the micronutrients are dispersed throughout the body for their many critical functions.

Energy for Fuel

Metabolism is the sum of the chemical reactions that occur within a living cell to maintain life. The mitochondrion of the cell is the work center in which all metabolic reactions take place. The two types of metabolism are **catabolism** and **anabolism.** Catabolism is the breaking down of large substances into smaller units. For example, breaking down stored glycogen into its smaller building blocks (i.e., glucose) is a catabolic reaction. Anabolism is the opposite; it is the process by which cells build large substances from smaller particles, such as building a complex protein from single amino acids.

catabolism the metabolic process of breaking down large substances to yield smaller building blocks.

anabolism the metabolic process of building large substances from smaller parts; the opposite of catabolism.

CLINICAL APPLICATIONS

THE SOMETIMES EMBARRASSING EFFECTS OF DIGESTION

After eating certain foods, some people complain of the discomfort or embarrassment of gas. Gas is a normal by-product of digestion, but when it becomes painful or apparent to others, it may become a physical and social dilemma.

The gastrointestinal tract normally holds approximately 3 oz of gas that moves along with the food mass and is silently absorbed into the bloodstream. Sometimes extra gas collects in the stomach or intestine, thereby creating an embarrassing—although usually harmless—situation.

Stomach Gas

Gas in the stomach results from trapped air bubbles. It occurs when a person eats too fast, drinks through a straw, or otherwise takes in extra air while eating. Burping releases some gas, but the following tips may help to avoid uncomfortable situations:

- Avoid carbonated beverages.
- Do not gulp.
- Chew with the mouth closed.
- Do not drink from a can or through a straw.
- Do not eat while overly nervous.

Intestinal Gas

The passing of gas from the intestine can be a social embarrassment. This gas forms in the colon, where bacteria attack undigested items and cause them to decompose and produce gas. Carbohydrates release hydrogen, carbon dioxide, and—in some people with certain types of bacteria in the gut—methane. All three products are odorless (although noisy) gases. Protein produces hydrogen sulfide and volatile compounds such as indole and skatole, which add a distinctive aroma to the expelled air. The following suggestions may help to control flatulence:

- Cut down on simple carbohydrates (e.g., sugars). Especially observe milk's effect, because lactose intolerance may be the culprit. Substitute cultured forms, such as yogurt or milk treated with a lactase product such as Lactaid (McNeil Nutritionals, Fort Washington, Pa).
- Use a prior leaching process before cooking dry beans to remove indigestible saccharides such as raffinose and stachyose. Although humans cannot digest these substances, they provide a feast for bacteria in the intestines. This simple procedure eliminates a major portion of these gas-forming saccharides. First, put washed, dry beans into a large pot, add 4 cups of water for each pound of beans (approximately 2 cups), and boil the beans uncovered for 2 minutes. Remove the pot from the heat, cover it, and let it stand for 1 hour. Finally, drain and rinse the beans, add 8 cups of fresh water, bring the water to a boil, reduce the heat, and simmer the beans in a covered pot for 1 to 2 hours or until beans are tender. Season as desired.
- Eliminate known food offenders. These vary from person to person, but some of the most common offenders are beans (if they are not prepared for cooking as described), onions, cabbage, and high-fiber wheat products.

When relief has been achieved, slowly add more complex carbohydrates and high-fiber foods back into the diet. After small amounts are tolerated, try moderate increases. If no relief occurs, medical help may be needed to rule out or treat an overactive gastrointestinal tract.

The Krebs cycle, which is also known as the *citric acid cycle* or the *TCA cycle*, is the hub of energy production that occurs in the mitochondria of the cell. The combined processes of metabolism (i.e., catabolic and anabolic reactions) ensure that the body has much needed energy in the form of adenosine triphosphate (ATP). The rate of ATP production fluctuates, and it speeds up or slows down depending on energy needs at a given time. Energy needs are minimal during sleep, but they increase dramatically during strenuous physical activity. Energy supply and demand are discussed further in Chapter 6. Figure 5-9 (on page 77) illustrates a brief breakdown of the macronutrients and how they enter the final step of energy production to ultimately supply cells with ATP.

Because carbohydrates have 4 kcal/g and fat has 9 kcal/g, the metabolism of glucose yields less energy (i.e., ATP) than the metabolism of fat, gram for gram. However, the body prefers to use glucose as its primary source of energy. Protein can be used as a source of energy as well, but this is a relatively inefficient method of producing energy, and it results in extra nitrogen waste. The body only breaks down protein for energy when glucose and fatty acids are in short supply.

Stored Energy

If the amount of food consumed yields more energy than is needed to maintain voluntary and involuntary actions,

TABLE 5-1 INTESTINAL ABSORPTION OF SOME MAJOR NUTRIENTS

Nutrient	Form	Means of Absorption	Control Agent or Required Cofactor	Route
Carbohydrate	Monosaccharides (glucose or galactose)	Competitive	—	Blood
		Selective	—	
		Active transport by sodium pump	Sodium	
	Fructose	Facilitated diffusion	Protein carrier	Blood
Protein	Amino acids	Selective	—	Blood
	Some dipeptides	Facilitated diffusion	Pyridoxine (pyridoxal phosphate)	Blood
	Whole protein (rare)	Pinocytosis	Protein carrier	Blood
Fat	Fatty acids	Fatty acid–bile complex (micelles)	Bile	Lymph
	Glycerides (monoglycerides and diglycerides)			
	Few triglycerides (neutral fat)	Pinocytosis	—	Lymph
Vitamins	B_{12}	Facilitated diffusion	Intrinsic factor	Blood
	A, D, E, and K	Bile complex (micelles)	Bile	Blood
	K from bacterial synthesis			From the large intestine to the blood
Minerals	Sodium	Active transport by sodium pump	—	Blood
	Calcium	Active transport	Vitamin D	Blood
	Iron	Active transport	Ferritin mechanism	Blood (as transferrin)
Water	Water	Osmosis	—	Blood, lymph, and interstitial fluid

the remaining energy is stored for later use in the body. The human body is a highly efficient organism. Energy or kilocalories in excess of needs are not wasted. Excess glucose can easily be stored as glycogen in the liver and muscles for quick energy at a later time. The anabolic process of converting extra glucose into glycogen is called ***glycogenesis***.

When the glycogen reserves are full, additional excess energy from carbohydrates, fat, or protein are stored as fat in adipose tissue. **Lipogenesis** is the building up of triglycerides for storage in the **adipose tissue** of the body. Both glycogen and stored fat are available for use when energy demands require it. Energy balance and the factors that influence it are discussed further in Chapter 6.

Excess protein intake is not stored as muscle. The body uses amino acids to build functional and structural proteins as needed, and the liver stores some free amino acids to meet rapid needs of the body. However, protein intake above and beyond the body's requirements is broken down further so that the nitrogen unit is removed, and the remaining carbon chain can be converted to glucose or fat for storage. The conversion of amino acids to glucose is referred to as ***gluconeogenesis***.

Although alcohol is not a nutrient, it does provide 7 kcal/g. Therefore, alcohol intake adds to the overall supply of energy (see the For Further Focus box, "What About Alcohol?").

ERRORS IN DIGESTION AND METABOLISM

The Genetic Defect

Certain food intolerances stem from underlying genetic disease. For each genetic disease, the necessary enzyme that controls the cell's metabolism of a specific nutrient

glycogenesis the anabolic process of creating stored glycogen from glucose.

lipogenesis the anabolic process of forming fat.

adipose tissue the storage site for excess fat.

gluconeogenesis the formation of glucose from non-carbohydrate substances such as amino acids.

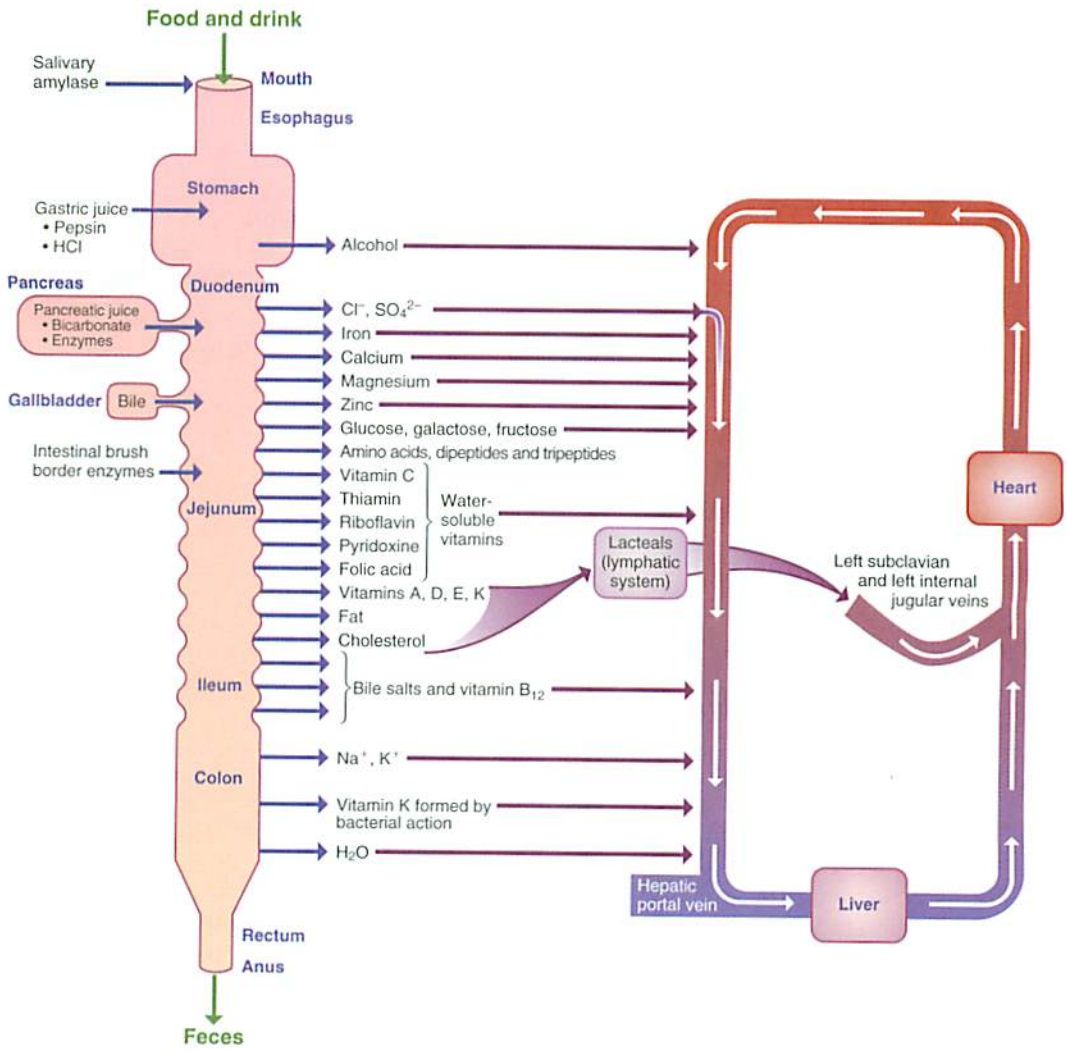

Figure 5-8 Sites of secretion and absorption in the gastrointestinal tract. (Mahan LK, Escott-Stump S. *Krause's food & nutrition therapy*. 12th ed. Philadelphia: Saunders; 2008.)

is missing, thereby preventing the normal nutrient metabolism. Three examples of genetic defects are phenylketonuria (PKU), galactosemia, and glycogen storage disease.

Phenylketonuria

PKU is an autosomal recessive genetic disorder that results when phenylalanine hydroxylase, which is the enzyme that is responsible for metabolizing the essential amino acid phenylalanine, is not produced by the body. If left untreated, this condition causes permanent mental retardation and central nervous system damage. Other possible symptoms and side effects include irritability, hyperactivity, convulsive seizures, and psychiatric disorders. PKU affects approximately 1 in every 10,000 to 15,000 live births in the United States. Screening tests began during the 1960s, and they are now mandatory at birth in all areas of the United States. A simple blood test can identify affected infants, and thus, treatment can start immediately. With proper treatment, children with PKU grow normally and have healthy lives. The treatment is a low-phenylalanine diet of special formulas and low-protein food products for life. Unfortunately, the prescribed diet is somewhat unpalatable, and lifelong adherence is low. Intensive family counseling by a metabolic team is needed. Research into cell-directed therapy and more permanent treatments is ongoing.[7]

Galactosemia

Galactosemia is a genetic disease that affects carbohydrate metabolism and that also results from a missing enzyme. Similar to PKU, galactosemia is an autosomal recessive

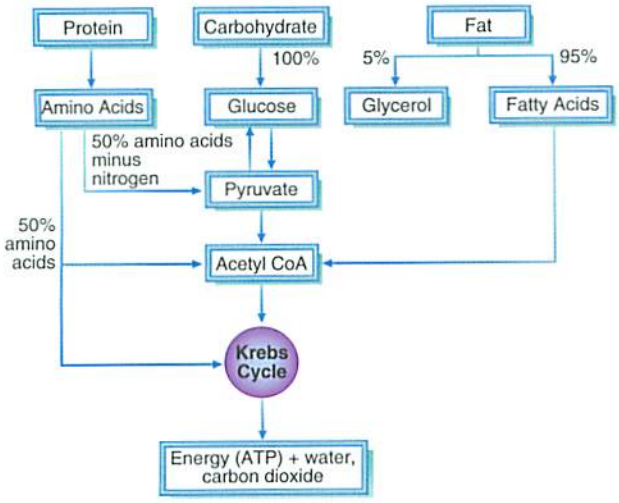

Figure 5-9 Metabolic pathways. (Reprinted from Peckenpaugh NJ. *Nutrition essentials and diet therapy.* 10th ed. Philadelphia: Saunders; 2007.)

disorder; it affects 1 in every 10,000 to 30,000 live births. The missing enzyme, galactose-1-phosphate uridyltransferase, is one that converts galactose to glucose. Because galactose comes from the breakdown of lactose (milk sugar), all sources of lactose in the diet must be eliminated. When it is not treated, galactosemia causes brain and liver damage. Newborn screening programs, which are required in all states, identify affected infants.[8] If treatment begins immediately, life-threatening damage may be avoided and thus, enable the child to grow normally. Treatment is a galactose-free diet, with special formulas for infants and lactose-free food guides. The treatment diet must be followed for life.

Glycogen Storage Diseases

Glycogen storage diseases (GSDs) are a group of rare genetic defects that inhibit the normal metabolic pathways of glycogen. This disease occurs in 1 of every 20,000 to 40,000 live births in the United States.[9] Twelve distinct forms of GSD result from the absence of the enzymes that are required for the synthesis or breakdown of glycogen. The specific form of GSD is distinguished by the enzyme

FOR FURTHER FOCUS

WHAT ABOUT ALCOHOL?

Does Alcohol Provide Energy?

Yes. Alcohol contributes to the overall energy intake in the form of calories. Alcohol yields 7 kcal/g consumed. This is more than both carbohydrates and protein, which yield 4 kcal/g each.

Is Alcohol a Nutrient?

No. Unlike carbohydrates, fats, proteins, vitamins, minerals, and water, alcohol performs no essential function in the body. Alcohol is not stored in the body, but the by-products of metabolism can accumulate to toxic amounts when alcohol is consumed in large quantities.

How Is Alcohol Digested?

The majority (i.e., 85% to 95%) of alcohol is absorbed without any chemical digestion. Alcohol is one of the few substances that can be absorbed directly into the circulation from the stomach. Small amounts of alcohol can enter the blood circulation from the mouth and the esophagus. What is not absorbed in the stomach is absorbed in the small intestine and sent directly to the liver for metabolism.

How Is Alcohol Metabolized?

Alcohol metabolism takes precedence over the metabolism of any other nutrient in the body because it is a toxin. The primary by-product of alcohol metabolism is acetaldehyde, which is the culprit for the destruction of healthy tissue that is associated with alcoholism. After detoxifying the alcohol, the liver uses remaining by-products to produce fatty acids. Fatty acids are combined with glycerol through lipogenesis to form triglycerides, and they are stored in the liver. A single drinking binge can result in an accumulation of fat in the liver. Repeated episodes over time can lead to fatty liver disease, which is the first stage of alcoholic liver disease.

Alcohol metabolism is a priority for the liver. Blood alcohol concentrations peak at approximately 30 to 45 minutes after one drink, which is defined as 12 oz of beer, 5 oz of wine, or 1.5 oz of 80-proof distilled spirits. The liver can only work so fast to metabolize and rid the body of alcohol, regardless of how much has been consumed. When consumption exceeds the rate of metabolism, alcohol and its metabolites begin to accumulate in the blood.

Several factors influence an individual's ability to metabolize alcohol, including gender, food intake, body weight, sex hormones, and medications.

More Information

To find out more about alcohol and its dangers, benefits, and associated diseases, refer to the following Web sites:

- Alcoholics Anonymous: www.aa.org
- The National Council on Alcoholism and Drug Dependence: www.ncadd.org
- National Institute on Alcohol Abuse and Alcoholism: www.niaaa.nih.gov

that is missing and the tissue affected. The liver is the primary site of glycogen metabolism; therefore, hepatic forms of GSD (e.g., von Gierke's disease or type I glycogenosis) affect the glucose availability of the whole body. Myopathic forms of GSD inhibit normal glycogen metabolism in the striated muscles, and they are less severe than hepatic forms. An example of a myopathic form is McArdle's disease (i.e., type V glycogenosis).

Other Intolerances or Allergies

Not all intolerances are genetic inborn errors of metabolism. Some problems with digestion and metabolism are the result of food intolerances or allergies. An example of a food intolerance that is caused by the inability to complete digestion is lactose intolerance.

Lactose Intolerance

A deficiency of any one of the disaccharidases (i.e., lactase, sucrase, or maltase) in the small intestine may produce a wide range of GI problems and abdominal pain because the specific sugar involved cannot be digested (see Chapter 2). Lactose intolerance is the most common, and it presents as varying degrees of intolerance. With this condition, there is insufficient lactase to break down the milk sugar lactose; thus, lactose accumulates in the intestine, causing abdominal cramping and diarrhea. Milk and all products containing lactose are carefully avoided. Milk that is treated with a commercial lactase product and soymilk products are safe substitutes.

Allergies

This chapter is limited to digestion, metabolism, transport, and absorption; therefore, allergic reactions (e.g., celiac disease) are not covered here. Allergies are inappropriate immune responses to substances that are not otherwise harmful and not necessarily problems with digestion or metabolism. Issues that are specific to GI disorders and allergies are covered in more detail in Chapter 18.

SUMMARY

- Necessary nutrients as they occur in food are not usable by the human body; they must be changed, released, regrouped, and rerouted into forms that body cells can use. The closely related activities of digestion, absorption, and transport ensure that key food nutrients are delivered to the cells so that the multiple metabolic tasks that sustain life can be completed.
- Mechanical digestion consists of spontaneous muscular activity that is responsible for the initial mechanical breakdown by mastication and the movement of the food mass along the GI tract by motions such as peristalsis.
- Chemical digestion involves enzymatic action that breaks food down into progressively smaller components and then releases its nutrients for absorption.
- Absorption involves the passage of nutrients from the intestines into the mucosal lining of the intestinal wall. It primarily occurs in the small intestine as a result of the work of highly efficient intestinal wall structures that, together with a number of effective absorbing mechanisms, increase the absorbent surface area. Nutrients that are absorbed are then transported throughout the body by the blood circulation.
- The nutrients that we eat are converted into ATP through the cycles of metabolism. Metabolism is the sum of the body processes that change food energy from the macronutrients into various forms of energy. Metabolism is a balance of both anabolic and catabolic reactions.
- Genetic diseases of metabolism result from missing enzymes that control the metabolism of specific nutrients. Special diets in each case limit or eliminate the particular nutrient involved.

CRITICAL THINKING QUESTIONS

1. Describe the types of muscle movement that are involved in mechanical digestion. What does the word *motility* mean?
2. Identify the digestive enzymes and any related substances secreted by the salivary and mucosal glands, the pancreas, and the liver. What activities do they perform on carbohydrates, proteins, and fats? What stimulates the release of these enzymes?
3. Describe four mechanisms of nutrient absorption from the small intestine. Describe the routes taken by the breakdown products of carbohydrates, proteins, and fats after absorption. Why must an alternate route to the bloodstream be provided for fat?
4. What functions does the large intestine perform?

CHAPTER CHALLENGE QUESTIONS

True-False

Write the correct statement for each statement that is false.

1. *True or False:* The digestive products of a large meal are difficult to absorb because the absorbent surface of the intestines is relatively small.
2. *True or False:* Before they can work, some enzymes must be activated by hydrochloric acid or another enzyme.
3. *True or False:* Bile is an enzyme that is specifically used for the chemical breakdown of fat.
4. *True or False:* The GI circulation provides a constant supply of water and electrolytes to carry digestive secretions and other substances.
5. *True or False:* Secretions from the GI accessory organs (i.e., the gallbladder and the pancreas) mix with gastric secretions in the stomach to help with digestion.
6. *True or False:* One enzyme may work on both carbohydrate and fat breakdown.
7. *True or False:* Bile is released from the gallbladder in response to a hormonal stimulus.

Multiple Choice

1. During digestion, the major muscle action that moves the food mass forward in regular rhythmic waves is called
   - **a.** valve contraction.
   - **b.** segmentation ring motion.
   - **c.** muscle tone.
   - **d.** peristalsis.
2. Mucus is an important GI secretion because it
   - **a.** causes chemical changes in substances to prepare for enzyme action.
   - **b.** helps to create the proper degree of acidity for enzymes to act.
   - **c.** lubricates and protects the GI lining.
   - **d.** helps to emulsify fats for enzyme action.
3. Pepsin is
   - **a.** produced in the small intestine to act on protein.
   - **b.** a gastric enzyme that acts on protein.
   - **c.** produced in the pancreas to act on fat.
   - **d.** produced in the small intestine to act on fat.
4. Bile is an important secretion that is
   - **a.** produced by the gallbladder.
   - **b.** stored in the liver.
   - **c.** an aid to protein digestion.
   - **d.** a fat-emulsifying agent.
5. The route of fat absorption is
   - **a.** the lymphatic system by way of the villi lacteals.
   - **b.** directly into the portal blood circulation.
   - **c.** with the aid of bile directly into the villi blood capillaries.
   - **d.** with the help of protein directly into the portal blood circulation.

Evolve Please refer to the Students' Resource section of this text's Evolve Web site for additional study resources.

REFERENCES

1. Food and Nutrition Board, Institute of Medicine. *Dietary reference intakes for calcium, phosphorous, magnesium, vitamin D, and fluoride.* Washington, DC: National Academies Press; 1997.
2. Food and Nutrition Board, Institute of Medicine. *Dietary reference intakes for thiamin, riboflavin, niacin, vitamin B6, folate, vitamin B12, pantothenic acid, biotin, and choline.* Washington, DC: National Academies Press; 2000.
3. Food and Nutrition Board, Institute of Medicine. *Dietary reference intakes for vitamin C, vitamin E, selenium, and carotenoids.* Washington, DC: National Academies Press; 2000.
4. Food and Nutrition Board, Institute of Medicine. *Dietary reference intakes for vitamin A, vitamin K, arsenic, boron, chromium, copper, iodine, iron, manganese, molybdenum, nickel, silicon, vanadium, and zinc.* Washington, DC: National Academies Press; 2001.
5. Food and Nutrition Board, Institute of Medicine. *Dietary reference intakes for energy, carbohydrate, fiber, fat, fatty acids, cholesterol, protein, and amino acids.* Washington, DC: National Academies Press; 2002.
6. Food and Nutrition Board, Institute of Medicine. *Dietary reference intakes for water, potassium, sodium, chloride, and sulfate*, Washington, DC: National Academies Press; 2004.
7. Harding C. Progress toward cell-directed therapy for phenylketonuria. *Clin Genet.* 2008;74(2):97-104.
8. Kaye CI, Committee on Genetics, Accurso F, et al. Introduction to the newborn screening fact sheets. *Pediatrics.* 2006; 118(3):1304-1312.
9. Mayatepek E, Hoffmann B, Meissner T. Inborn errors of carbohydrate metabolism. *Best Pract Res Clin Gastroenterol* 2010;24(5):607-618.

FURTHER READING AND RESOURCES

The following organizations provide up-to-date research and reliable information about matters of the GI tract and metabolism.

The American College of Gastroenterology. www.acg.gi.org

The American Gastroenterological Association. www.gastro.org

The American Journal of Gastroenterology. www.amjgastro.com

Metabolism. www.metabolism.com

Nutrition & Metabolism. www.nutritionandmetabolism.com

Duggan S, O'Sullivan M, Feehan S, et al. Nutrition treatment of deficiency and malnutrition in chronic pancreatitis: a review. *Nutr Clin Pract*. 2010;25(4):362-370.

This article will give the reader insight into the complex issues that result when one accessory organ fails to provide the necessary enzymes for normal digestion.