

51

Fueling Body Activities: Digestion

Concept Outline

51.1 Animals employ a digestive system to prepare food for assimilation by cells.

Types of Digestive Systems. Some invertebrates have a gastrovascular cavity, but vertebrates have a digestive tract that chemically digests and absorbs the food.

Vertebrate Digestive Systems. The different regions of the gastrointestinal tract are adapted for different functions.

51.2 Food is ingested, swallowed, and transported to the stomach.

The Mouth and Teeth. Carnivores, herbivores, and omnivores display differences in the structure of their teeth.

Esophagus and Stomach. The esophagus delivers food to the stomach, which secretes hydrochloric acid and pepsin.

51.3 The small and large intestines have very different functions.

The Small Intestine. The small intestine has mucosal folds called villi and smaller folds called microvilli that absorb glucose, amino acids, and fatty acids into the blood.

The Large Intestine. The large intestine absorbs water, ions, and vitamin K, and excretes what remains as feces.

Variations in Vertebrate Digestive Systems. Digestive systems are adapted to particular diets.

51.4 Accessory organs, neural stimulation, and endocrine secretions assist in digestion.

Accessory Organs. The pancreas secretes digestive enzymes and the hormones insulin and glucagon. The liver produces bile, which emulsifies fat; the gallbladder stores the bile.

Neural and Hormonal Regulation of Digestion. Nerves and hormones help regulate digestive functions.

51.5 All animals require food energy and essential nutrients.

Food Energy and Energy Expenditure. The intake of food energy must balance the energy expended by the body in order to maintain a stable weight.

Essential Nutrients. Food must contain vitamins, minerals, and specific amino acids and fatty acids for health.



FIGURE 51.1

Animals are heterotrophs. All animals must consume plant material or other animals in order to live. The nuts in this chipmunk's cheeks will be consumed and converted to body tissue, energy, and refuse.

Plants and other photosynthetic organisms can produce the organic molecules they need from inorganic components. Therefore, they are autotrophs, or self-sustaining. Animals are heterotrophs: they must consume organic molecules present in other organisms (figure 51.1). The molecules heterotrophs eat must be digested into smaller molecules in order to be absorbed into the animal's body. Once these products of digestion enter the body, the animal can use them for energy in cell respiration or for the construction of the larger molecules that make up its tissues. The process of animal digestion is the focus of this chapter.

51.1 Animals employ a digestive system to prepare food for assimilation by cells.

Types of Digestive Systems

Heterotrophs are divided into three groups on the basis of their food sources. Animals that eat plants exclusively are classified as **herbivores**; common examples include cows, horses, rabbits and sparrows. Animals that are meat-eaters, such as cats, eagles, trout, and frogs, are **carnivores**. **Omnivores** are animals that eat both plants and other animals. Humans are omnivores, as are pigs, bears, and crows.

Single-celled organisms (as well as sponges) digest their food intracellularly. Other animals digest their food extracellularly, within a digestive cavity. In this case, the digestive enzymes are released into a cavity that is continuous with the animal's external environment. In coelenterates and flatworms (such as *Planaria*), the digestive cavity has only one opening that serves as both mouth and anus. There can be no specialization within this type of digestive system, called a *gastrovascular cavity*, because every cell is exposed to all stages of food digestion (figure 51.2).

Specialization occurs when the digestive tract, or alimentary canal, has a separate mouth and anus, so that transport of food is one-way. The most primitive digestive tract is seen in nematodes (phylum Nematoda), where it is simply a tubular *gut* lined by an epithelial membrane. Earthworms (phylum Annelida) have a digestive tract spe-

cialized in different regions for the ingestion, storage, fragmentation, digestion, and absorption of food. All higher animal groups, including all vertebrates, show similar specializations (figure 51.3).

The ingested food may be stored in a specialized region of the digestive tract or may first be subjected to physical fragmentation. This fragmentation may occur through the chewing action of teeth (in the mouth of many vertebrates), or the grinding action of pebbles (in the gizzard of earthworms and birds). Chemical digestion then occurs, breaking down the larger food molecules of polysaccharides and disaccharides, fats, and proteins into their smallest subunits. Chemical digestion involves hydrolysis reactions that liberate the subunit molecules—primarily monosaccharides, amino acids, and fatty acids—from the food. These products of chemical digestion pass through the epithelial lining of the gut into the blood, in a process known as absorption. Any molecules in the food that are not absorbed cannot be used by the animal. These waste products are excreted, or defecated, from the anus.

Most animals digest their food extracellularly. The digestive tract, with a one-way transport of food and specialization of regions for different functions, allows food to be ingested, physically fragmented, chemically digested, and absorbed.

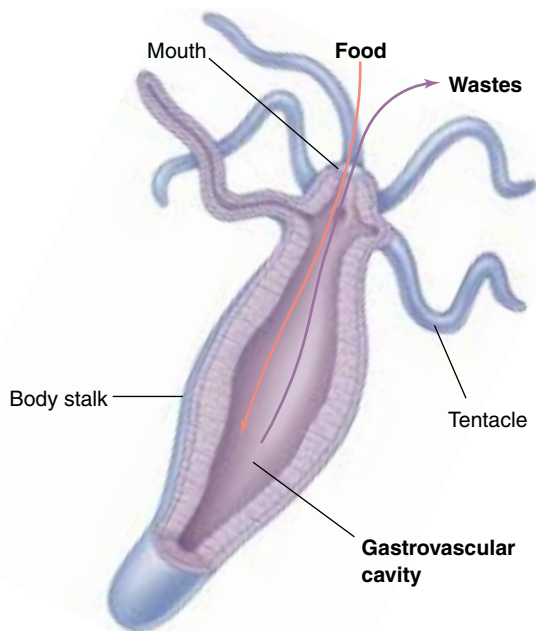


FIGURE 51.2
The gastrovascular cavity of *Hydra*, a coelenterate. Because there is only one opening, the mouth is also the anus, and no specialization is possible in the different regions that participate in extracellular digestion.

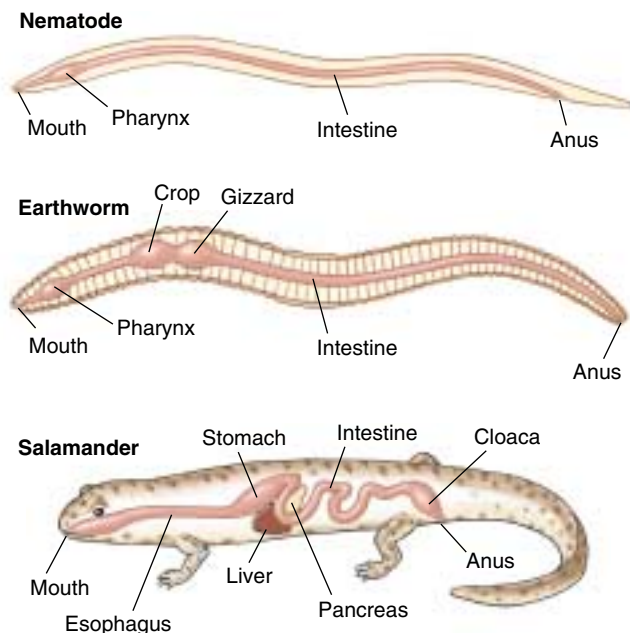


FIGURE 51.3
The one-way digestive tract of nematodes, earthworms, and vertebrates. One-way movement through the digestive tract allows different regions of the digestive system to become specialized for different functions.

Vertebrate Digestive Systems

In humans and other vertebrates, the digestive system consists of a tubular gastrointestinal tract and accessory digestive organs (figure 51.4). The initial components of the gastrointestinal tract are the mouth and the pharynx, which is the common passage of the oral and nasal cavities. The pharynx leads to the esophagus, a muscular tube that delivers food to the stomach, where some preliminary digestion occurs. From the stomach, food passes to the first part of the small intestine, where a battery of digestive enzymes continues the digestive process. The products of digestion then pass across the wall of the small intestine into the bloodstream. The small intestine empties what remains into the large intestine, where water and minerals are absorbed. In most vertebrates other than mammals, the waste products emerge from the large intestine into a cavity called the cloaca (see figure 51.3), which also receives the products of the urinary and reproductive systems. In mammals, the urogenital products are separated from the fecal material in the large intestine; the fecal material enters the rectum and is expelled through the anus.

In general, carnivores have shorter intestines for their size than do herbivores. A short intestine is adequate for a carnivore, but herbivores ingest a large amount of plant cellulose, which resists digestion. These animals have a long, convoluted small intestine. In addition, mammals called *ruminants* (such as cows) that consume grass and other vegetation have stomachs with multiple chambers, where bacteria aid in the digestion of cellulose. Other herbivores, including rabbits and horses, digest cellulose (with the aid of bacteria) in a blind pouch called the **cecum** located at the beginning of the large intestine.

The accessory digestive organs (described in detail later in the chapter) include the liver, which produces *bile* (a green solution that emulsifies fat), the gallbladder, which stores and concentrates the bile, and the pancreas. The pancreas produces *pancreatic juice*, which contains digestive enzymes and bicarbonate. Both bile and pancreatic juice are secreted into the first region of the small intestine and aid digestion.

The tubular gastrointestinal tract of a vertebrate has a characteristic layered structure (figure 51.5). The innermost layer is the mucosa, an epithelium that lines the interior of the tract (the lumen). The next major tissue layer, made of connective tissue, is called the submucosa. Just outside the submucosa is the muscularis, which consists of a double layer of smooth muscles. The muscles in the inner layer have a circular orientation, and those in the outer layer are arranged longitudinally. Another connective tissue layer, the serosa, covers the external surface of the tract. Nerves, intertwined in regions called *plexuses*, are located in the submucosa and help regulate the gastrointestinal activities.

The vertebrate digestive system consists of a tubular gastrointestinal tract, which is modified in different animals, composed of a series of tissue layers.

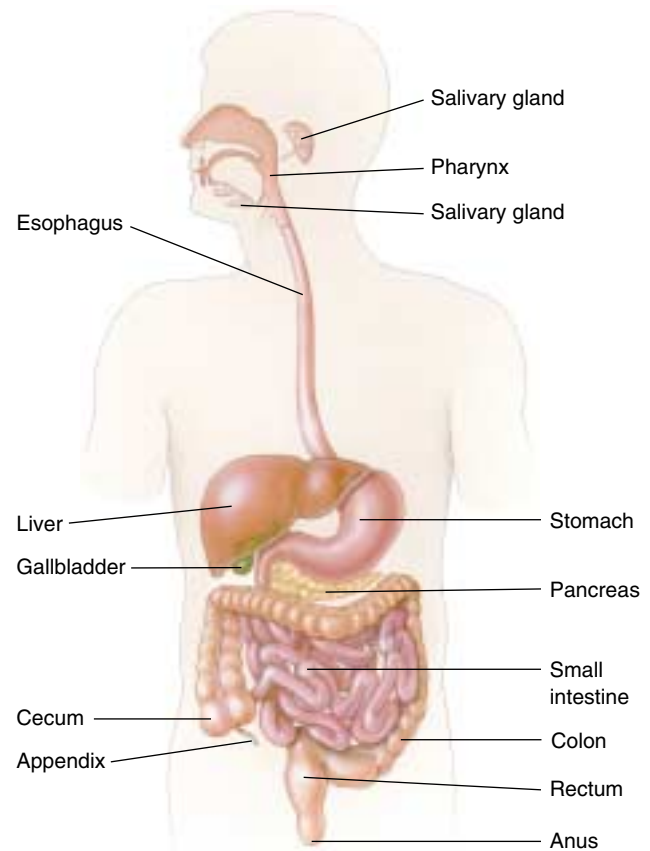


FIGURE 51.4
The human digestive system. Humans, like all placental mammals, lack a cloaca and have a separate exit from the digestive tract through the rectum and anus.

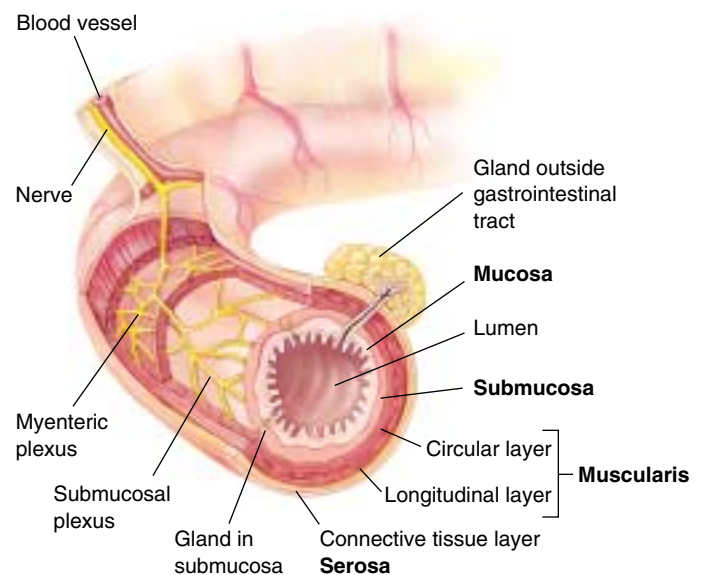


FIGURE 51.5
The layers of the gastrointestinal tract. The mucosa contains a lining epithelium; the submucosa is composed of connective tissue (as is the serosa), and the muscularis consists of smooth muscles.

51.2 Food is ingested, swallowed, and transported to the stomach.

The Mouth and Teeth

Specializations of the digestive systems in different kinds of vertebrates reflect differences in the way these animals live. Fishes have a large pharynx with gill slits, while air-breathing vertebrates have a greatly reduced pharynx. Many vertebrates have teeth (figure 51.6), and chewing (*mastication*) breaks up food into small particles and mixes it with fluid secretions. Birds, which lack teeth, break up food in their two-chambered stomachs (figure 51.7). In one of these chambers, the gizzard, small pebbles ingested by the bird are churned together with the food by muscular action. This churning grinds up the seeds and other hard plant material into smaller chunks that can be digested more easily.

Vertebrate Teeth

Carnivorous mammals have pointed teeth that lack flat grinding surfaces. Such teeth are adapted for cutting and shearing. Carnivores often tear off pieces of their prey but have little need to chew them, because digestive enzymes can act directly on animal cells. (Recall how a cat or dog gulps down its food.) By contrast, grass-eating herbivores, such as cows and horses, must pulverize the cellulose cell walls of plant tissue before digesting it. These animals have large, flat teeth with complex ridges well-suited to grinding.

Human teeth are specialized for eating both plant and animal food. Viewed simply, humans are carnivores in the front of the mouth and herbivores in the back (figure 51.8). The four front teeth in the upper and lower jaws are sharp, chisel-shaped incisors used for biting. On each side of the incisors are sharp, pointed teeth called cuspids (sometimes referred to as “canine” teeth), which are used for tearing food. Behind the canines are two premolars and three molars, all with flattened, ridged surfaces for grinding and crushing food. Children have only 20 teeth, but these deciduous teeth are lost during childhood and are replaced by 32 adult teeth.

The Mouth

Inside the mouth, the tongue mixes food with a mucous solution, saliva. In humans, three pairs of salivary glands secrete saliva into the mouth through ducts in the mouth’s mucosal lining. Saliva moistens and lubricates the food so that it is easier to swallow and does not abrade the tissue it passes on its way through the esophagus. Saliva also contains the hydrolytic enzyme salivary amylase, which initiates the breakdown of the polysaccharide starch into the disaccharide maltose. This digestion is usually minimal in humans, however, because most people don’t chew their food very long.

The secretions of the salivary glands are controlled by the nervous system, which in humans maintains a constant

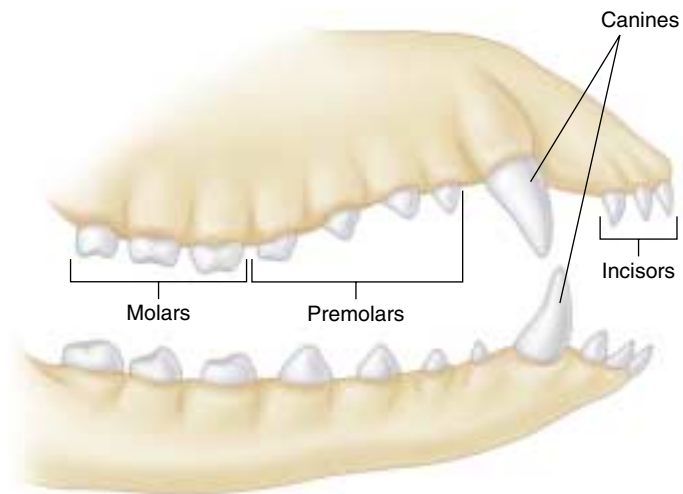


FIGURE 51.6
Diagram of generalized vertebrate dentition. Different vertebrates will have specific variations from this generalized pattern, depending on whether the vertebrate is an herbivore, carnivore, or omnivore.

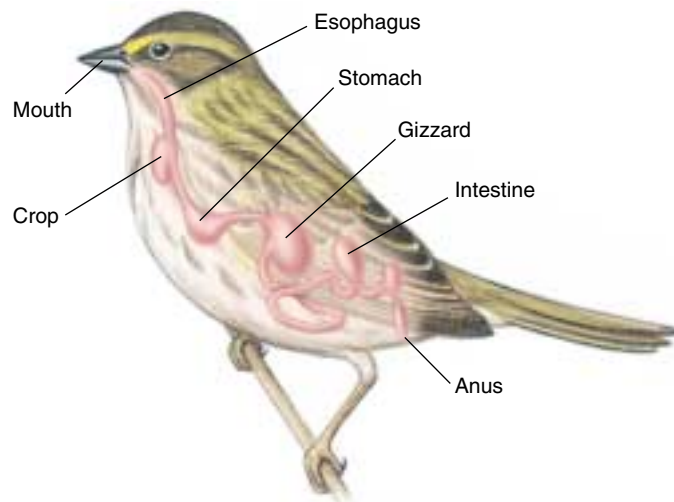


FIGURE 51.7
Birds store food in the crop and grind it up in the gizzard. Birds lack teeth but have a muscular chamber called the gizzard that works to break down food. Birds swallow gritty objects or pebbles that lodge in the gizzard and pulverize food before it passes into the small intestine.

flow of about half a milliliter per minute when the mouth is empty of food. This continuous secretion keeps the mouth moist. The presence of food in the mouth triggers an increased rate of secretion, as taste-sensitive neurons in the mouth send impulses to the brain, which responds by stimulating the salivary glands. The most potent stimuli are

acidic solutions; lemon juice, for example, can increase the rate of salivation eightfold. The sight, sound, or smell of food can stimulate salivation markedly in dogs, but in humans, these stimuli are much less effective than thinking or talking about food.

When food is ready to be swallowed, the tongue moves it to the back of the mouth. In mammals, the process of swallowing begins when the soft palate elevates, pushing against the back wall of the pharynx (figure 51.9). Elevation of the soft palate seals off the nasal cavity and prevents food from entering it. Pressure against the pharynx triggers an automatic, involuntary response called a reflex. In this reflex, pressure on the pharynx stimulates neurons within its walls, which send impulses to the swallowing center in the brain. In response, electrical impulses in motor neurons stimulate muscles to contract and raise the *larynx* (voice box). This pushes the *glottis*, the opening from the larynx into the trachea (windpipe), against a flap of tissue called the *epiglottis*. These actions keep food out of the respiratory tract, directing it instead into the esophagus.

In many vertebrates ingested food is fragmented through the tearing or grinding action of specialized teeth. In birds, this is accomplished through the grinding action of pebbles in the gizzard. Food mixed with saliva is swallowed and enters the esophagus.

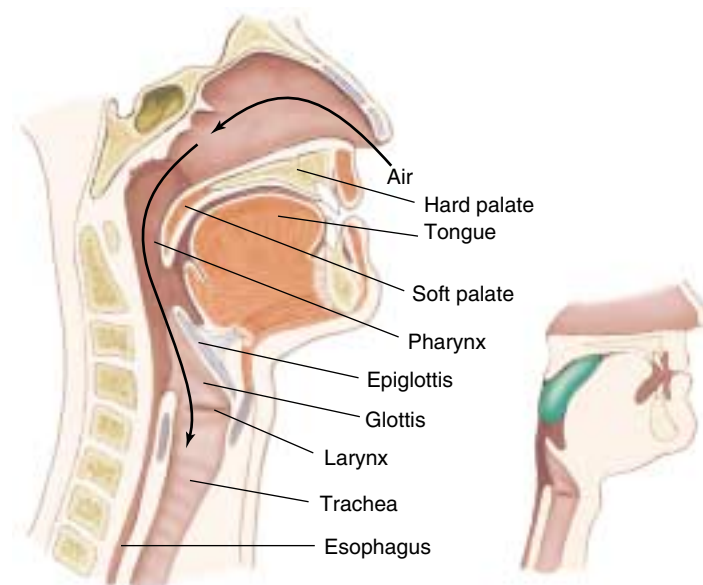


FIGURE 51.9
The human pharynx, palate, and larynx. Food that enters the pharynx is prevented from entering the nasal cavity by elevation of the soft palate, and is prevented from entering the larynx and trachea (the airways of the respiratory system) by elevation of the larynx against the epiglottis.

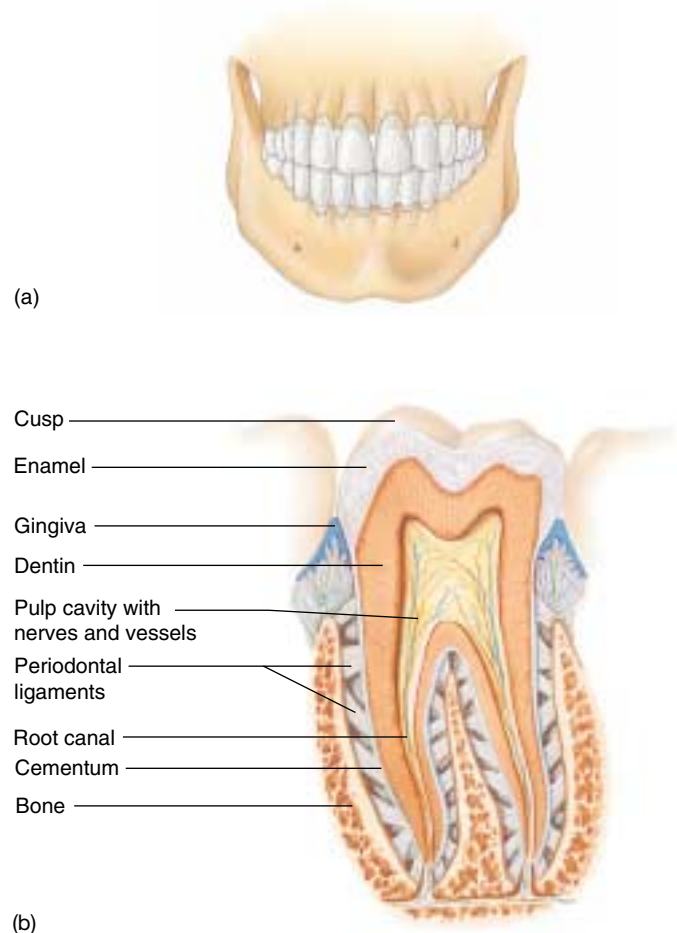
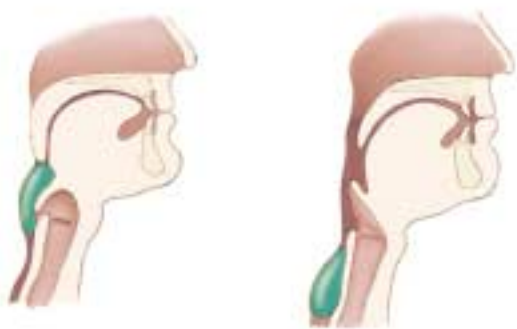


FIGURE 51.8
Human teeth. (a) The front six teeth on the upper and lower jaws are cuspids and incisors. The remaining teeth, running along the sides of the mouth, are grinders called premolars and molars. Hence, humans have carnivore-like teeth in the front of their mouth and herbivore-like teeth in the back. (b) Each tooth is alive, with a central pulp containing nerves and blood vessels. The actual chewing surface is a hard enamel layered over the softer dentin, which forms the body of the tooth.



Esophagus and Stomach

Structure and Function of the Esophagus

Swallowed food enters a muscular tube called the esophagus, which connects the pharynx to the stomach. In adult humans, the esophagus is about 25 centimeters long; the upper third is enveloped in skeletal muscle, for voluntary control of swallowing, while the lower two-thirds is surrounded by involuntary smooth muscle. The swallowing center stimulates successive waves of contraction in these muscles that move food along the esophagus to the stomach. These rhythmic waves of muscular contraction are called peristalsis (figure 51.10); they enable humans and other vertebrates to swallow even if they are upside down.

In many vertebrates, the movement of food from the esophagus into the stomach is controlled by a ring of circular smooth muscle, or a *sphincter*, that opens in response to the pressure exerted by the food. Contraction of this sphincter prevents food in the stomach from moving back into the esophagus. Rodents and horses have a true sphincter at this site and thus cannot regurgitate, while humans lack a true sphincter and so are able to regurgitate. Normally, however, the human esophagus is closed off except during swallowing.

Structure and Function of the Stomach

The stomach (figure 51.11) is a saclike portion of the digestive tract. Its inner surface is highly convoluted, enabling it to fold up when empty and open out like an expanding balloon as it fills with food. Thus, while the human stomach has a volume of only about 50 milliliters when empty, it may expand to contain 2 to 4 liters of food when full. Carnivores that engage in sporadic gorging as an important survival strategy possess stomachs that are able to distend much more than that.

Secretory Systems

The stomach contains an extra layer of smooth muscle for churning food and mixing it with *gastric juice*, an acidic secretion of the tubular gastric glands of the mucosa (figure 51.11). These exocrine glands contain two kinds of secretory cells: parietal cells, which secrete hydrochloric acid (HCl); and chief cells, which secrete pepsinogen, a weak protease (protein-digesting enzyme) that requires a very low pH to be active. This low pH is provided by the HCl. Activated pepsinogen molecules then cleave one another at specific sites, producing a much more active protease, pepsin. This process of secreting a relatively inactive enzyme that is then converted into a more active enzyme outside the cell prevents the chief cells from digesting themselves. It should be noted that only proteins are partially digested in the stomach—there is no significant digestion of carbohydrates or fats.

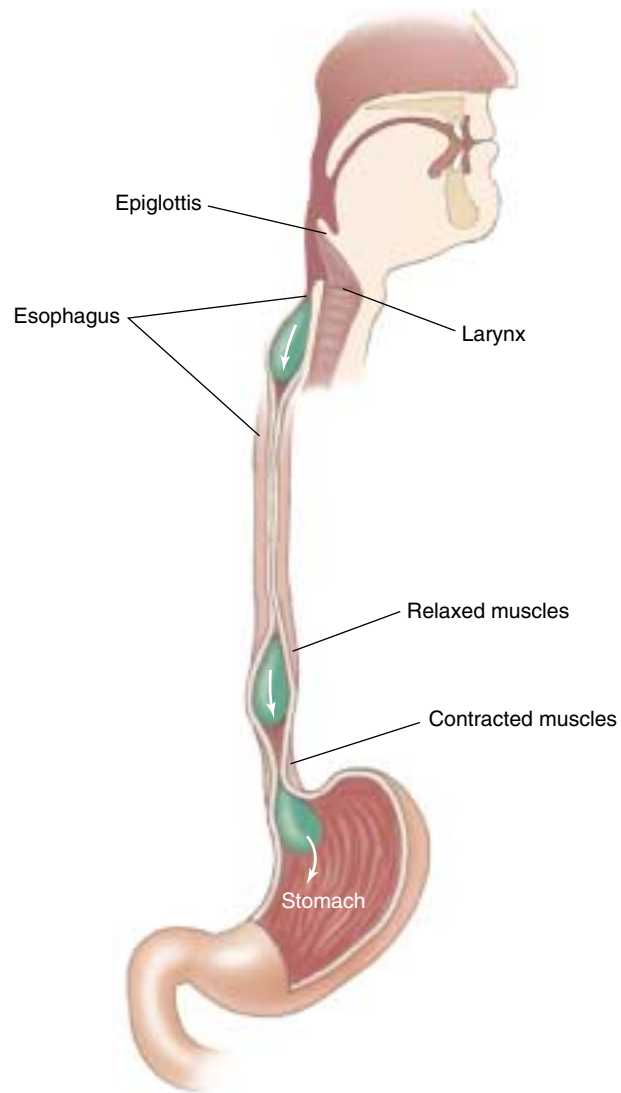


FIGURE 51.10
The esophagus and peristalsis. After food has entered the esophagus, rhythmic waves of muscular contraction, called peristalsis, move the food down to the stomach.

Action of Acid

The human stomach produces about 2 liters of HCl and other gastric secretions every day, creating a very acidic solution inside the stomach. The concentration of HCl in this solution is about 10 millimolar, corresponding to a pH of 2. Thus, gastric juice is about 250,000 times more acidic than blood, whose normal pH is 7.4. The low pH in the stomach helps denature food proteins, making them easier to digest, and keeps pepsin maximally active. Active pepsin hydrolyzes food proteins into shorter chains of polypeptides that are not fully digested until the mixture enters the small intestine. The mixture of partially digested food and gastric juice is called chyme.

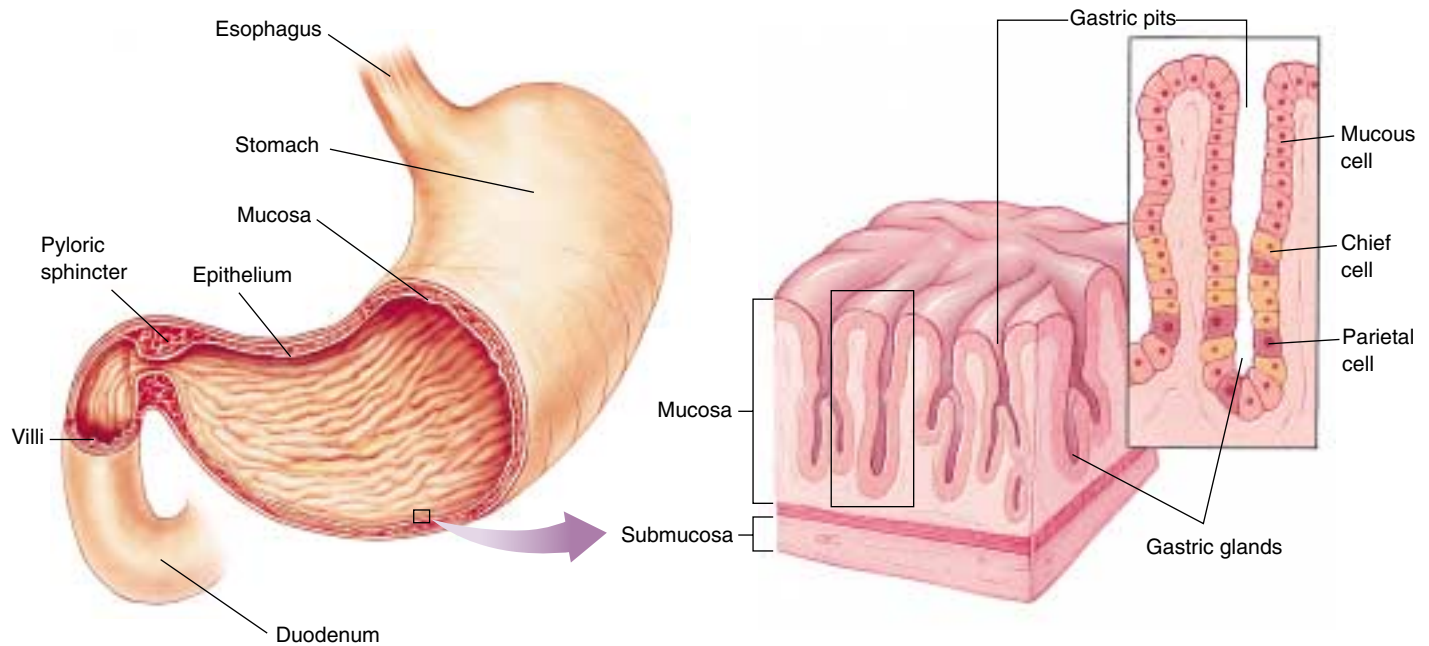


FIGURE 51.11

The stomach and duodenum. Food enters the stomach from the esophagus. A band of smooth muscle called the pyloric sphincter controls the entrance to the duodenum, the upper part of the small intestine. The epithelial walls of the stomach are dotted with gastric pits, which contain gastric glands that secrete hydrochloric acid and the enzyme pepsinogen. The gastric glands consist of mucous cells, chief cells that secrete pepsinogen, and parietal cells that secrete HCl. Gastric pits are the openings of the gastric glands.

The acidic solution within the stomach also kills most of the bacteria that are ingested with the food. The few bacteria that survive the stomach and enter the intestine intact are able to grow and multiply there, particularly in the large intestine. In fact, most vertebrates harbor thriving colonies of bacteria within their intestines, and bacteria are a major component of feces. As we will discuss later, bacteria that live within the digestive tract of cows and other ruminants play a key role in the ability of these mammals to digest cellulose.

Ulcers

Overproduction of gastric acid can occasionally eat a hole through the wall of the stomach. Such *gastric ulcers* are rare, however, because epithelial cells in the mucosa of the stomach are protected somewhat by a layer of alkaline mucus, and because those cells are rapidly replaced by cell division if they become damaged (gastric epithelial cells are replaced every 2 to 3 days). Over 90% of gastrointestinal ulcers are *duodenal ulcers*. These may be produced when excessive amounts of acidic chyme are delivered into the duodenum, so that the acid cannot be properly neutralized through the action of alkaline pancreatic juice (described later). Susceptibility to ulcers is increased when the mucosal barriers to self-digestion are weakened by an infection of the bacterium *Helicobacter pylori*. Indeed, modern

antibiotic treatments of this infection can reduce symptoms and often even cure the ulcer.

In addition to producing HCl, the parietal cells of the stomach also secrete intrinsic factor, a polypeptide needed for the intestinal absorption of vitamin B₁₂. Because this vitamin is required for the production of red blood cells, persons who lack sufficient intrinsic factor develop a type of anemia (low red blood cell count) called *pernicious anemia*.

Leaving the Stomach

Chyme leaves the stomach through the *pyloric sphincter* (see figure 51.11) to enter the small intestine. This is where all terminal digestion of carbohydrates, lipids, and proteins occurs, and where the products of digestions—amino acids, glucose, and so on—are absorbed into the blood. Only some of the water in chyme and a few substances such as aspirin and alcohol are absorbed through the wall of the stomach.

Peristaltic waves of contraction propel food along the esophagus to the stomach. Gastric juice contains strong hydrochloric acid and the protein-digesting enzyme pepsin, which begins the digestion of proteins into shorter polypeptides. The acidic chyme is then transferred through the pyloric sphincter to the small intestine.

51.3 The small and large intestines have very different functions.

The Small Intestine

Digestion in the Small Intestine

The capacity of the small intestine is limited, and its digestive processes take time. Consequently, efficient digestion requires that only relatively small amounts of chyme be introduced from the stomach into the small intestine at any one time. Coordination between gastric and intestinal activities is regulated by neural and hormonal signals, which we will describe in a later section.

The small intestine is approximately 4.5 meters long in a living person, but is 6 meters long at autopsy when the muscles relax. The first 25 centimeters is the **duodenum**; the remainder of the small intestine is divided into the **jejunum** and the **ileum**. The duodenum receives acidic chyme from the stomach, digestive enzymes and bicarbonate from the pancreas, and bile from the liver and gallbladder. The pancreatic juice enzymes digest larger food molecules into smaller fragments. This occurs primarily in the duodenum and jejunum.

The epithelial wall of the small intestine is covered with tiny, fingerlike projections called villi (singular, villus; figure

51.12). In turn, each of the epithelial cells lining the villi is covered on its apical surface (the side facing the lumen) by many foldings of the plasma membrane that form cytoplasmic extensions called *microvilli*. These are quite tiny and can be seen clearly only with an electron microscope (figure 51.13). In a light micrograph, the microvilli resemble the bristles of a brush, and for that reason the epithelial wall of the small intestine is also called a brush border.

The villi and microvilli greatly increase the surface area of the small intestine; in humans, this surface area is 300 square meters! It is over this vast surface that the products of digestion are absorbed. The microvilli also participate in digestion because a number of digestive enzymes are embedded within the epithelial cells' plasma membranes, with their active sites exposed to the chyme (figure 51.14). These brush border enzymes include those that hydrolyze the disaccharides lactose and sucrose, among others (table 51.1). Many adult humans lose the ability to produce the brush border enzyme *lactase* and therefore cannot digest lactose (milk sugar), a rather common condition called *lactose intolerance*. The brush border enzymes complete the digestive process that started with the action of the pancreatic enzymes released into the duodenum.

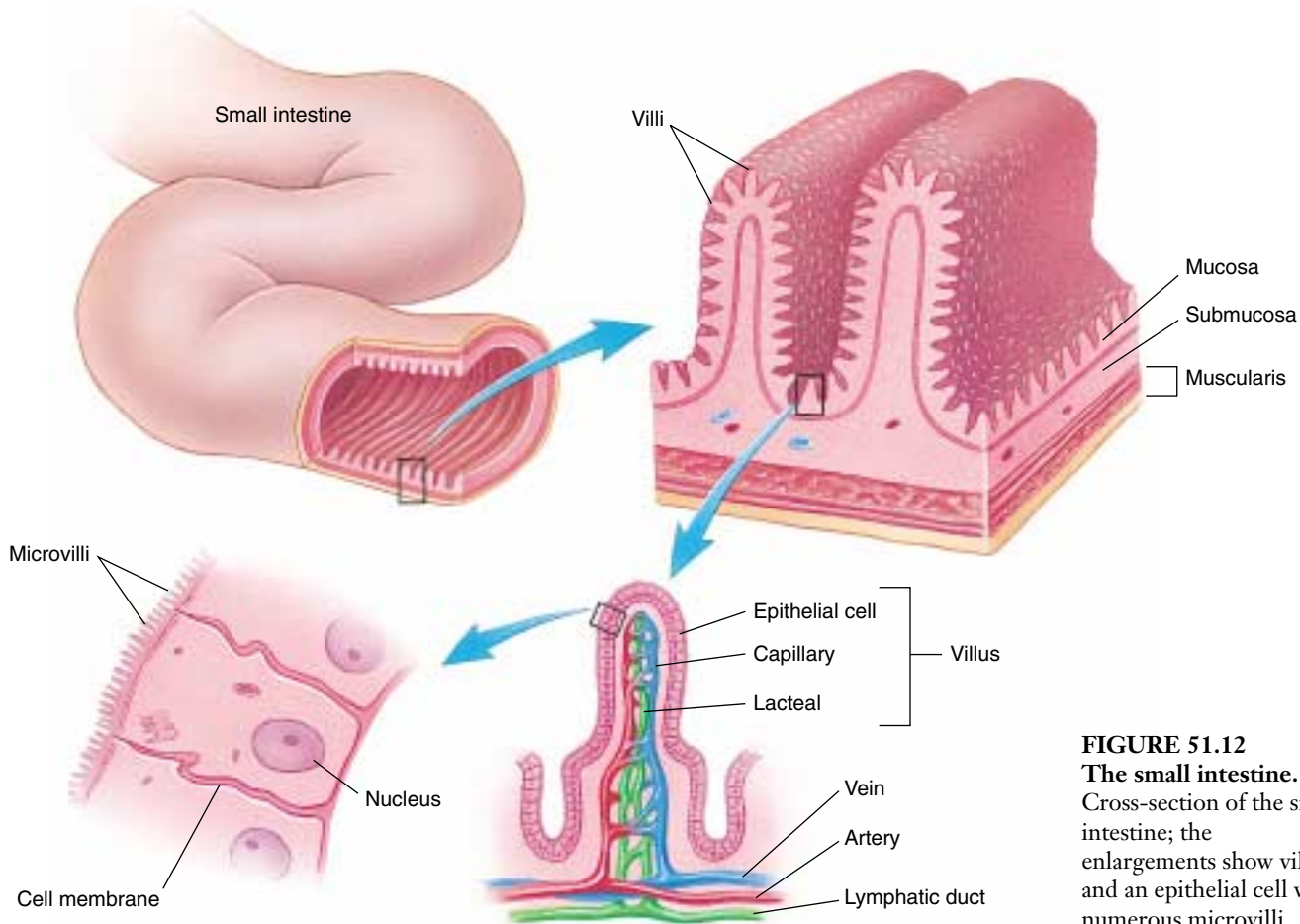


FIGURE 51.12
The small intestine. Cross-section of the small intestine; the enlargements show villi and an epithelial cell with numerous microvilli.

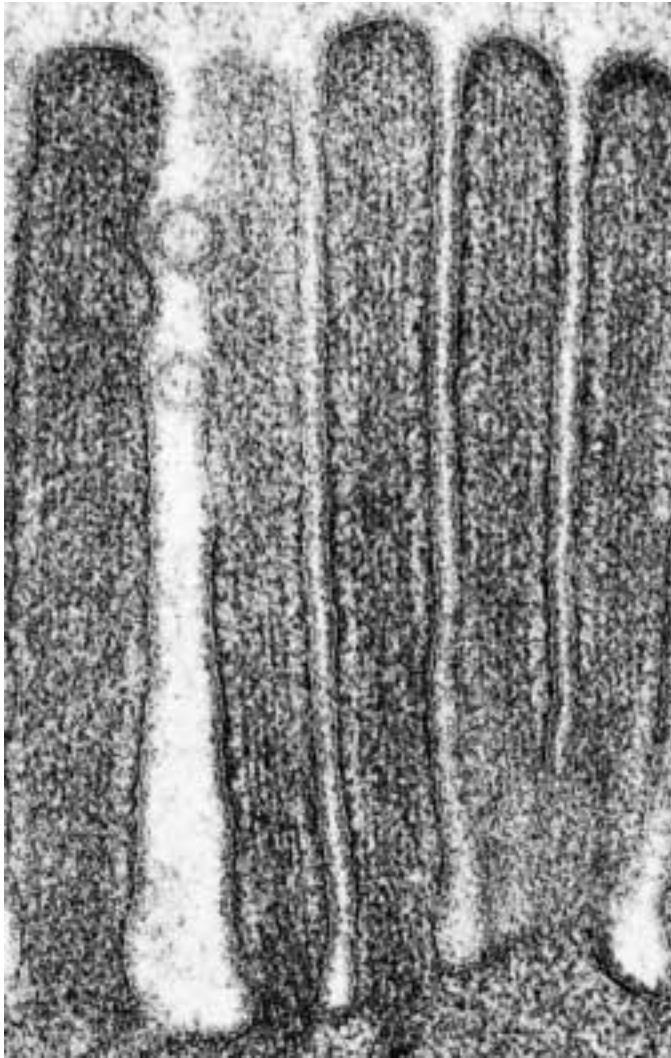


FIGURE 51.13
Intestinal microvilli. Microvilli, shown in an electron micrograph, are very densely clustered, giving the small intestine an enormous surface area important in efficient absorption of the digestion products.

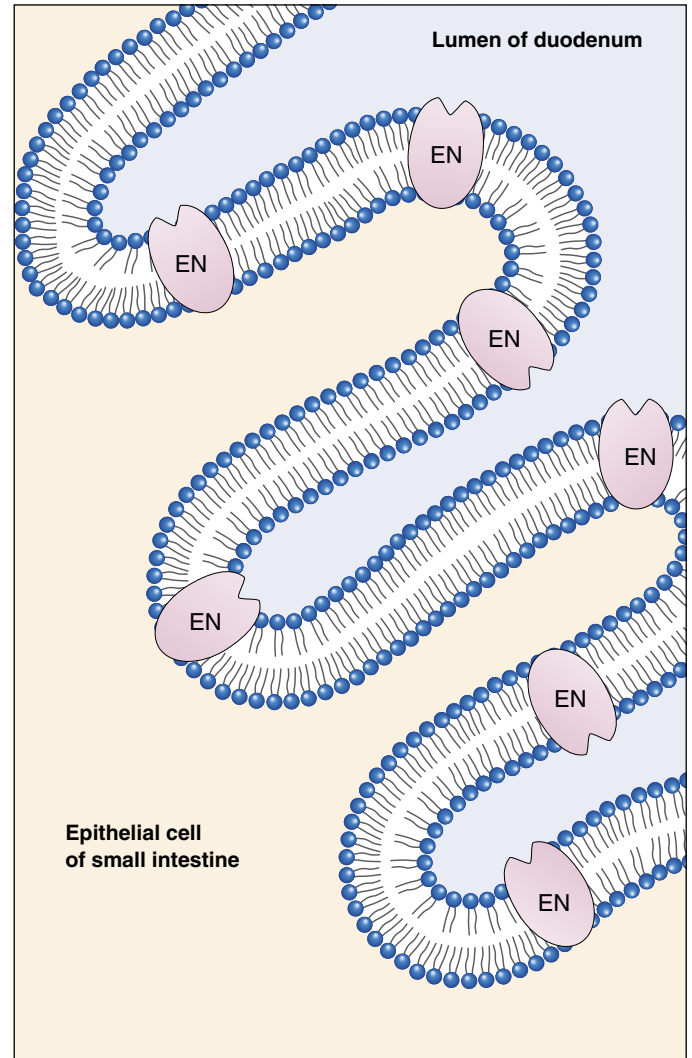


FIGURE 51.14
Brush border enzymes. These enzymes, which are labeled “EN” in this diagram, are part of the plasma membrane of the microvilli in the small intestine. They catalyze many of the terminal steps in digestion.

Table 51.1 Digestive Enzymes

Location	Enzymes	Substrates	Digestion Products
Salivary glands	Amylase	Starch, glycogen	Disaccharides
Stomach	Pepsin	Proteins	Short peptides
Small intestine (brush border)	Peptidases	Short peptides	Amino acids
	Nucleases	DNA, RNA	Sugars, nucleic acid bases
	Lactase, maltase, sucrase	Disaccharides	Monosaccharides
Pancreas	Lipase	Triglycerides	Fatty acids, glycerol
	Trypsin, chymotrypsin	Proteins	Peptides
	DNase	DNA	Nucleotides
	RNase	RNA	Nucleotides

Absorption in the Small Intestine

The amino acids and monosaccharides resulting from the digestion of proteins and carbohydrates, respectively, are transported across the brush border into the epithelial cells that line the intestine (figure 51.15*a*). They then move to the other side of the epithelial cells, and from there are transported across the membrane and into the blood capillaries within the villi. The blood carries these products of digestion from the intestine to the liver via the hepatic portal vein. The term *portal* here refers to a special arrangement of vessels, seen only in a couple of instances, where one organ (the liver, in this case) is located “downstream” from another organ (the intestine). As a result, the second organ receives blood-borne molecules from the first. Because of the hepatic portal vein, the liver is the first organ to receive most of the products of digestion. This arrangement is important for the functions of the liver, as will be described in a later section.

The products of fat digestion are absorbed by a different mechanism (figure 51.15*b*). Fats (triglycerides) are hydrolyzed into fatty acids and monoglycerides, which are absorbed into the intestinal epithelial cells and reassembled into triglycerides. The triglycerides then combine with proteins to form small particles called chylomicrons. In-

stead of entering the hepatic portal circulation, the chylomicrons are absorbed into lymphatic capillaries (see chapter 52), which empty their contents into the blood in veins near the neck. Chylomicrons can make the blood plasma appear cloudy if a sample of blood is drawn after a fatty meal.

The amount of fluid passing through the small intestine in a day is startlingly large: approximately 9 liters. However, almost all of this fluid is absorbed into the body rather than eliminated in the feces. About 8.5 liters are absorbed in the small intestine and an additional 350 milliliters in the large intestine. Only about 50 grams of solid and 100 milliliters of liquid leave the body as feces. The normal fluid absorption efficiency of the human digestive tract thus approaches 99%, which is very high indeed.

Digestion occurs primarily in the duodenum, which receives the pancreatic juice enzymes. The small intestine provides a large surface area for absorption. Glucose and amino acids from food are absorbed through the small intestine and enter the blood via the hepatic portal vein, going to the liver. Fat from food enters the lymphatic system.

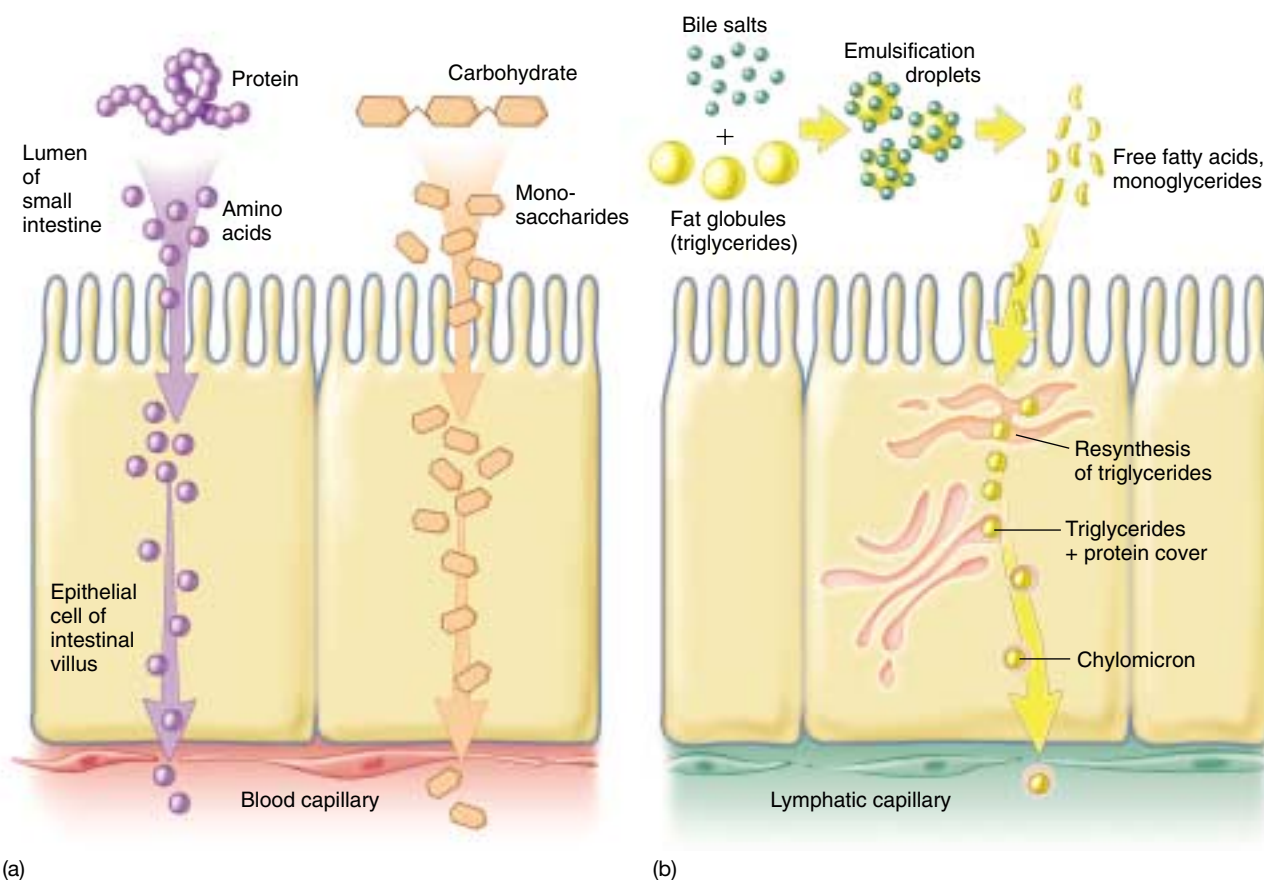


FIGURE 51.15

Absorption of the products of digestion. (a) Monosaccharides and amino acids are transported into blood capillaries. (b) Fatty acids and monoglycerides within the intestinal lumen are absorbed and converted within the intestinal epithelial cells into triglycerides. These are then coated with proteins to form tiny structures called chylomicrons, which enter lymphatic capillaries.

The Large Intestine

The large intestine, or colon, is much shorter than the small intestine, occupying approximately the last meter of the digestive tract; it is called “large” only because of its larger diameter. The small intestine empties directly into the large intestine at a junction where two vestigial structures, the cecum and the appendix, remain (figure 51.16). No digestion takes place within the large intestine, and only about 4% of the absorption of fluids by the intestine occurs there. The large intestine is not as convoluted as the small intestine, and its inner surface has no villi. Consequently, the large intestine has less than one-thirtieth the absorptive surface area of the small intestine. Although sodium, vitamin K, and some products of bacterial metabolism are absorbed across its wall, the primary function of the large intestine is to concentrate waste material. Within it, undigested material, primarily bacterial fragments and cellulose, is compacted and stored. Many bacteria live and reproduce within the large intestine, and the excess bacteria are incorporated into the refuse material, called *feces*. Bacterial fermentation produces gas within the colon at a rate of about 500 milliliters per day. This rate increases greatly after the consumption of beans or other vegetable matter because the passage of undigested plant material (fiber) into the large intestine provides substrates for fermentation.

The human colon has evolved to process food with a relatively high fiber content. Diets that are low in fiber, which are common in the United States, result in a slower passage of food through the colon. Low dietary fiber content is thought to be associated with the level of colon cancer in the United States, which is among the highest in the world.

Compacted feces, driven by peristaltic contractions of the large intestine, pass from the large intestine into a short tube called the rectum. From the rectum, the feces exit the body through the anus. Two sphincters control passage through the anus. The first is composed of smooth muscle and opens involuntarily in response to pressure inside the rectum. The second, composed of striated muscle, can be controlled voluntarily by the brain, thus permitting a conscious decision to delay defecation.

In all vertebrates except most mammals, the reproductive and urinary tracts empty together with the digestive tract into a common cavity, the cloaca. In some reptiles and birds, additional water from either the feces or urine may be absorbed in the cloaca before the products are expelled from the body.

The large intestine concentrates wastes for excretion by absorbing water. Some ions and vitamin K are also absorbed by the large intestine.

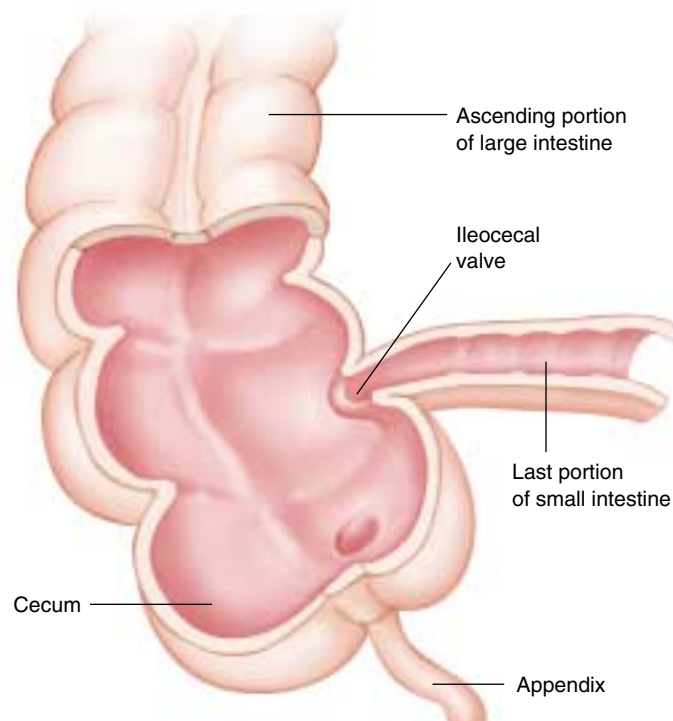


FIGURE 51.16

The junction of the small and large intestines in humans. The large intestine, or colon, starts with the cecum, which is relatively small in humans compared with that in other mammals. A vestigial structure called the appendix extends from the cecum.

Variations in Vertebrate Digestive Systems

Most animals lack the enzymes necessary to digest cellulose, the carbohydrate that functions as the chief structural component of plants. The digestive tracts of some animals, however, contain bacteria and protists that convert cellulose into substances the host can digest. Although digestion by gastrointestinal microorganisms plays a relatively small role in human nutrition, it is an essential element in the nutrition of many other kinds of animals, including insects like termites and cockroaches, and a few groups of herbivorous mammals. The relationships between these microorganisms and their animal hosts are mutually beneficial and provide an excellent example of symbiosis.

Cows, deer, and other ruminants have large, divided stomachs (figure 51.17). The first portion consists of the rumen and a smaller chamber, the reticulum; the second portion consists of two additional chambers: the omasum and abomasum. The rumen which may hold up to 50 gallons, serves as a fermentation vat in which bacteria and protozoa convert cellulose and other molecules into a variety of simpler compounds. The location of the rumen at the front of the four chambers is important because it allows the animal to regurgitate and rechew the contents of the rumen, an activity called *ruminating*, or “chewing the cud.” The cud is then swallowed and enters the reticulum, from which it passes to the omasum and then the abomasum, where it is finally mixed with gastric juice. Hence, only the abomasum is equivalent to the human stomach in its function. This process leads to a far more efficient digestion of cellulose in ruminants than in mammals that lack a rumen, such as horses.

In horses, rodents, and lagomorphs (rabbits and hares), the digestion of cellulose by microorganisms takes place in the cecum, which is greatly enlarged (figure 51.18). Because the cecum is located beyond the stomach, regurgitation of its contents is impossible. However, rodents and lagomorphs have evolved another way to digest cellulose that achieves a degree of efficiency similar to that of ruminant digestion. They do this by eating their feces, thus passing the food through their digestive tract a second time. The second passage makes it possible for the animal to absorb the nutrients produced by the microorganisms in its cecum. Animals that engage in this practice of **coprophagy** (from the Greek words *copros*, “excrement,” and *phagein*, “eat”) cannot remain healthy if they are prevented from eating their feces.

Cellulose is not the only plant product that vertebrates can use as a food source because of the digestive activities

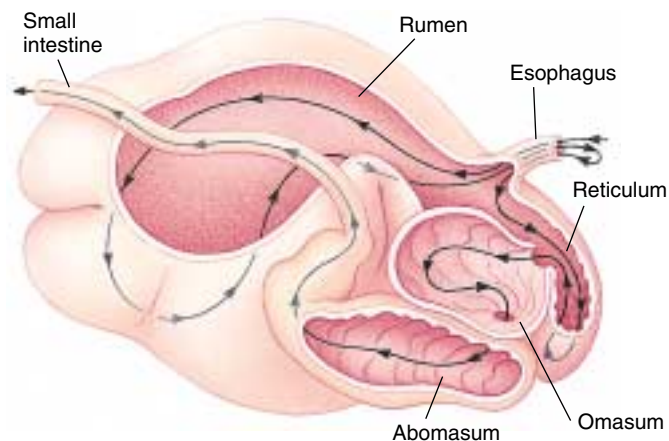


FIGURE 51.17
Four-chambered stomach of a ruminant. The grass and other plants that a ruminant, such as a cow, eats enter the rumen, where they are partially digested. Before moving into a second chamber, the reticulum, the food may be regurgitated and rechewed. The food is then transferred to the rear two chambers: the omasum and abomasum. Only the abomasum is equivalent to the human stomach in its function of secreting gastric juice.

of intestinal microorganisms. Wax, a substance indigestible by most terrestrial animals, is digested by symbiotic bacteria living in the gut of honey guides, African birds that eat the wax in bee nests. In the marine food chain, wax is a major constituent of copepods (crustaceans in the plankton), and many marine fish and birds appear to be able to digest wax with the aid of symbiotic microorganisms.

Another example of the way intestinal microorganisms function in the metabolism of their animal hosts is provided by the synthesis of vitamin K. All mammals rely on intestinal bacteria to synthesize this vitamin, which is necessary for the clotting of blood. Birds, which lack these bacteria, must consume the required quantities of vitamin K in their food. In humans, prolonged treatment with antibiotics greatly reduces the populations of bacteria in the intestine; under such circumstances, it may be necessary to provide supplementary vitamin K.

Much of the food value of plants is tied up in cellulose, and the digestive tract of many animals harbors colonies of cellulose-digesting microorganisms. Intestinal microorganisms also produce molecules such as vitamin K that are important to the well-being of their vertebrate hosts.

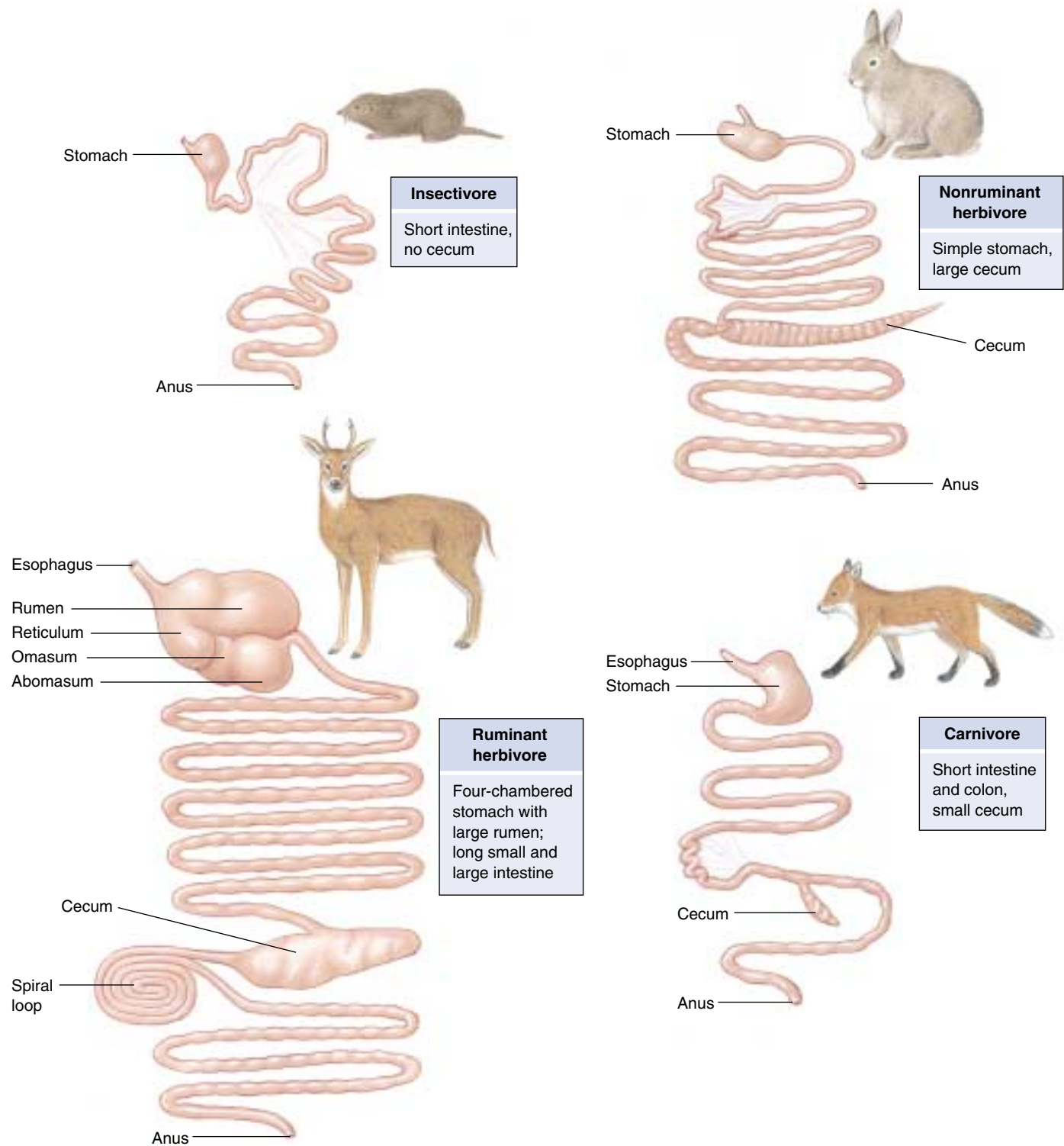


FIGURE 51.18

The digestive systems of different mammals reflect their diets. Herbivores require long digestive tracts with specialized compartments for the breakdown of plant matter. Protein diets are more easily digested; thus, insectivorous and carnivorous mammals have short digestive tracts with few specialized pouches.

51.4 Accessory organs, neural stimulation, and endocrine secretions assist in digestion.

Accessory Organs

Secretions of the Pancreas

The pancreas (figure 51.19), a large gland situated near the junction of the stomach and the small intestine, is one of the accessory organs that contribute secretions to the digestive tract. Pancreatic fluid is secreted into the duodenum through the *pancreatic duct*; thus, the pancreas functions as an exocrine organ. This fluid contains a host of enzymes, including trypsin and chymotrypsin, which digest proteins; pancreatic amylase, which digests starch; and lipase, which digests fat. These enzymes are released into the duodenum primarily as inactive zymogens and are then activated by the brush border enzymes of the intestine. Pancreatic enzymes digest proteins into smaller polypeptides, polysaccharides into shorter chains of sugars, and fat into free fatty acids and other products. The digestion of these molecules is then completed by the brush border enzymes.

Pancreatic fluid also contains bicarbonate, which neutralizes the HCl from the stomach and gives the chyme in the duodenum a slightly alkaline pH. The digestive enzymes and bicarbonate are produced by clusters of secretory cells known as *acini*.

In addition to its exocrine role in digestion, the pancreas also functions as an endocrine gland, secreting several hormones into the blood that control the blood levels of glucose and other nutrients. These hormones are produced in the **islets of Langerhans**, clusters of endocrine cells scattered throughout the pancreas. The two most important pancreatic hormones, insulin and glucagon, are discussed later in this chapter.

The Liver and Gallbladder

The liver is the largest internal organ of the body (see figure 51.4). In an adult human, the liver weighs about 1.5 kilograms and is the size of a football. The main exocrine secretion of the liver is bile, a fluid mixture consisting of *bile pigments* and *bile salts* that is delivered into the duodenum during the digestion of a meal. The bile pigments do not participate in digestion; they are waste products resulting from the liver's destruction of old red blood cells and

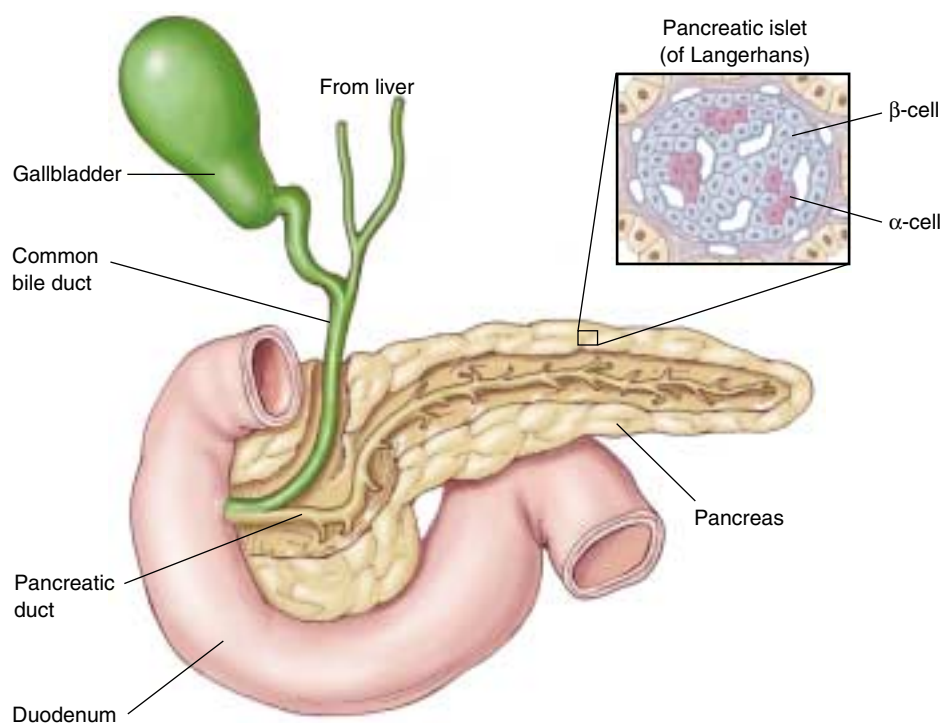


FIGURE 51.19

The pancreas and bile duct empty into the duodenum. The pancreas secretes pancreatic juice into the pancreatic duct. The pancreatic islets of Langerhans secrete hormones into the blood; α -cells secrete glucagon and β -cells secrete insulin.

ultimately are eliminated with the feces. If the excretion of bile pigments by the liver is blocked, the pigments can accumulate in the blood and cause a yellow staining of the tissues known as *jaundice*.

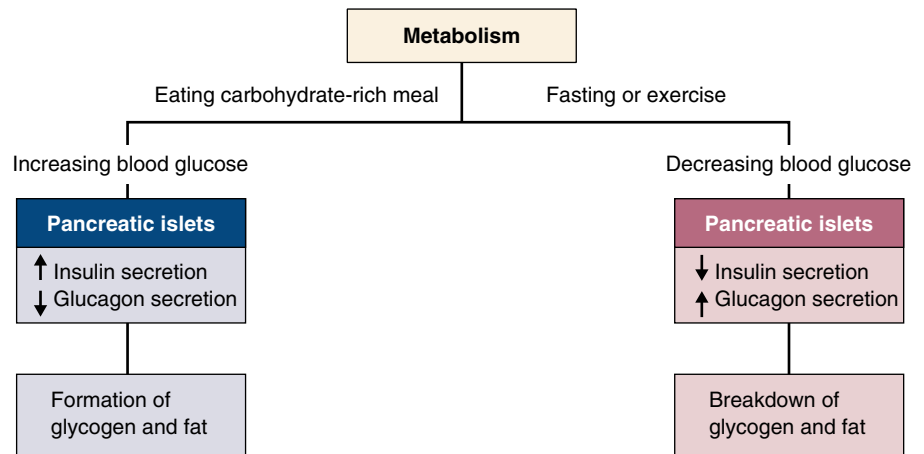
In contrast, the bile salts play a very important role in the digestion of fats. Because fats are insoluble in water, they enter the intestine as drops within the watery chyme. The bile salts, which are partly lipid-soluble and partly water-soluble, work like detergents, dispersing the large drops of fat into a fine suspension of smaller droplets. This emulsification process produces a greater surface area of fat upon which the lipase enzymes can act, and thus allows the digestion of fat to proceed more rapidly.

After it is produced in the liver, bile is stored and concentrated in the gallbladder. The arrival of fatty food in the duodenum triggers a neural and endocrine reflex (discussed later) that stimulates the gallbladder to contract, causing bile to be transported through the common bile duct and injected into the duodenum. If the bile duct is blocked by a *gallstone* (formed from a hardened precipitate of cholesterol), contraction of the gallbladder will cause pain generally felt under the right scapula (shoulder blade).

FIGURE 51.20

The actions of insulin and glucagon.

After a meal, an increased secretion of insulin by the β cells of the pancreatic islets promotes the deposition of glycogen and fat. During fasting or exercising, an increased glucagon secretion by the α cells of the pancreatic islets and a decreased insulin secretion promote the breakdown (through hydrolysis reactions) of glycogen and fat.



Regulatory Functions of the Liver

Because the hepatic portal vein carries blood from the stomach and intestine directly to the liver, the liver is in a position to chemically modify the substances absorbed in the gastrointestinal tract before they reach the rest of the body. For example, ingested alcohol and other drugs are taken into liver cells and metabolized; this is why the liver is often damaged as a result of alcohol and drug abuse. The liver also removes toxins, pesticides, carcinogens, and other poisons, converting them into less toxic forms. An important example of this is the liver's conversion of the toxic ammonia produced by intestinal bacteria into urea, a compound that can be contained safely and carried by the blood at higher concentrations.

Similarly, the liver regulates the levels of many compounds produced within the body. Steroid hormones, for instance, are converted into less active and more water-soluble forms by the liver. These molecules are then included in the bile and eliminated from the body in the feces, or carried by the blood to the kidneys and excreted in the urine.

The liver also produces most of the proteins found in blood plasma. The total concentration of plasma proteins is significant because it must be kept within normal limits in order to maintain osmotic balance between blood and interstitial (tissue) fluid. If the concentration of plasma proteins drops too low, as can happen as a result of liver disease such as cirrhosis, fluid accumulates in the tissues, a condition called *edema*.

Regulation of Blood Glucose Concentration

The neurons in the brain obtain their energy primarily from the aerobic respiration of glucose obtained from the blood plasma. It is therefore extremely important that the

blood glucose concentration not fall too low, as might happen during fasting or prolonged exercise. It is also important that the blood glucose concentration not stay at too high a level, as it does in people with uncorrected *diabetes mellitus*, because this can lead to tissue damage.

After a carbohydrate-rich meal, the liver and skeletal muscles remove excess glucose from the blood and store it as the polysaccharide glycogen. This process is stimulated by the hormone insulin, secreted by the β (*beta*) cells in the islets of Langerhans of the pancreas. When blood glucose levels decrease, as they do between meals, during periods of fasting, and during exercise, the liver secretes glucose into the blood. This glucose is obtained in part from the breakdown of liver glycogen to glucose-6-phosphate, a process called glycogenolysis. The phosphate group is then removed, and free glucose is secreted into the blood. Skeletal muscles lack the enzyme needed to remove the phosphate group, and so, even though they have glycogen stores, they cannot secrete glucose into the blood. The breakdown of liver glycogen is stimulated by another hormone, glucagon, which is secreted by the α (*alpha*) cells of the islets of Langerhans in the pancreas (figure 51.20).

If fasting or exercise continues, the liver begins to convert other molecules, such as amino acids and lactic acid, into glucose. This process is called **gluconeogenesis** (“new formation of glucose”). The amino acids used for gluconeogenesis are obtained from muscle protein, which explains the severe muscle wasting that occurs during prolonged fasting.

The pancreas secretes digestive enzymes and bicarbonate into the pancreatic duct. The liver produces bile, which is stored and concentrated in the gallbladder. The liver and the pancreatic hormones regulate blood glucose concentration.

Neural and Hormonal Regulation of Digestion

The activities of the gastrointestinal tract are coordinated by the nervous system and the endocrine system. The nervous system, for example, stimulates salivary and gastric secretions in response to the sight and smell of food. When food arrives in the stomach, proteins in the food stimulate the secretion of a stomach hormone called gastrin (table 51.2), which in turn stimulates the secretion of pepsinogen and HCl from the gastric glands (figure 51.21). The secreted HCl then lowers the pH of the gastric juice, which acts to inhibit further secretion of gastrin. Because inhibition of gastrin secretion will reduce the amount of HCl released into the gastric juice, a negative feedback loop is completed. In this way, the secretion of gastric acid is kept under tight control.

The passage of chyme from the stomach into the duodenum inhibits the contractions of the stomach, so that no additional chyme can enter the duodenum until the previous amount has been processed. This inhibition is mediated by a neural reflex and by a hormone secreted by the small intestine that inhibits gastric emptying. The hormone is known generically as an enterogastrone (*entero* refers to the intestine; *gastro* to the stomach). The chemical identity of the enterogastrone is currently controver-

sial. A hormone known as gastric inhibitory peptide (GIP), released by the duodenum, was named for this function but may not be the only, or even the major, enterogastrone. The secretion of enterogastrone is stimulated most strongly by the presence of fat in the chyme. Fatty meals therefore remain in the stomach longer than meals low in fat.

The duodenum secretes two additional hormones. Cholecystokinin (CCK), like enterogastrone, is secreted in response to the presence of fat in the chyme. CCK stimulates the contractions of the gallbladder, injecting bile into the duodenum so that fat can be emulsified and more efficiently digested. The other duodenal hormone is secretin. Released in response to the acidity of the chyme that arrives in the duodenum, secretin stimulates the pancreas to release bicarbonate, which then neutralizes some of the acidity. Secretin has the distinction of being the first hormone ever discovered.

Neural and hormonal reflexes regulate the activity of the digestive system. The stomach's secretions are regulated by food and by the hormone gastrin. Other hormones, secreted by the duodenum, inhibit stomach emptying and promote the release of bile from the gallbladder and the secretion of bicarbonate in pancreatic juice.

Table 51.2 Hormones of Digestion

Hormone	Class	Source	Stimulus	Action	Note
Gastrin	Polypeptide	Pyloric portion of stomach	Entry of food into stomach	Stimulates secretion of HCl and pepsinogen by stomach	Unusual in that it acts on same organ that secretes it
Cholecystokinin	Polypeptide	Duodenum	Fatty chyme in duodenum	Stimulates gallbladder contraction and secretion of digestive enzymes by pancreas	Structurally similar to gastrin
Gastric inhibitory peptide	Polypeptide	Duodenum	Fatty chyme in duodenum	Inhibits stomach emptying	Also stimulates insulin secretion
Secretin	Polypeptide	Duodenum	Acidic chyme in duodenum	Stimulates secretion of bicarbonate by pancreas	The first hormone to be discovered (1902)

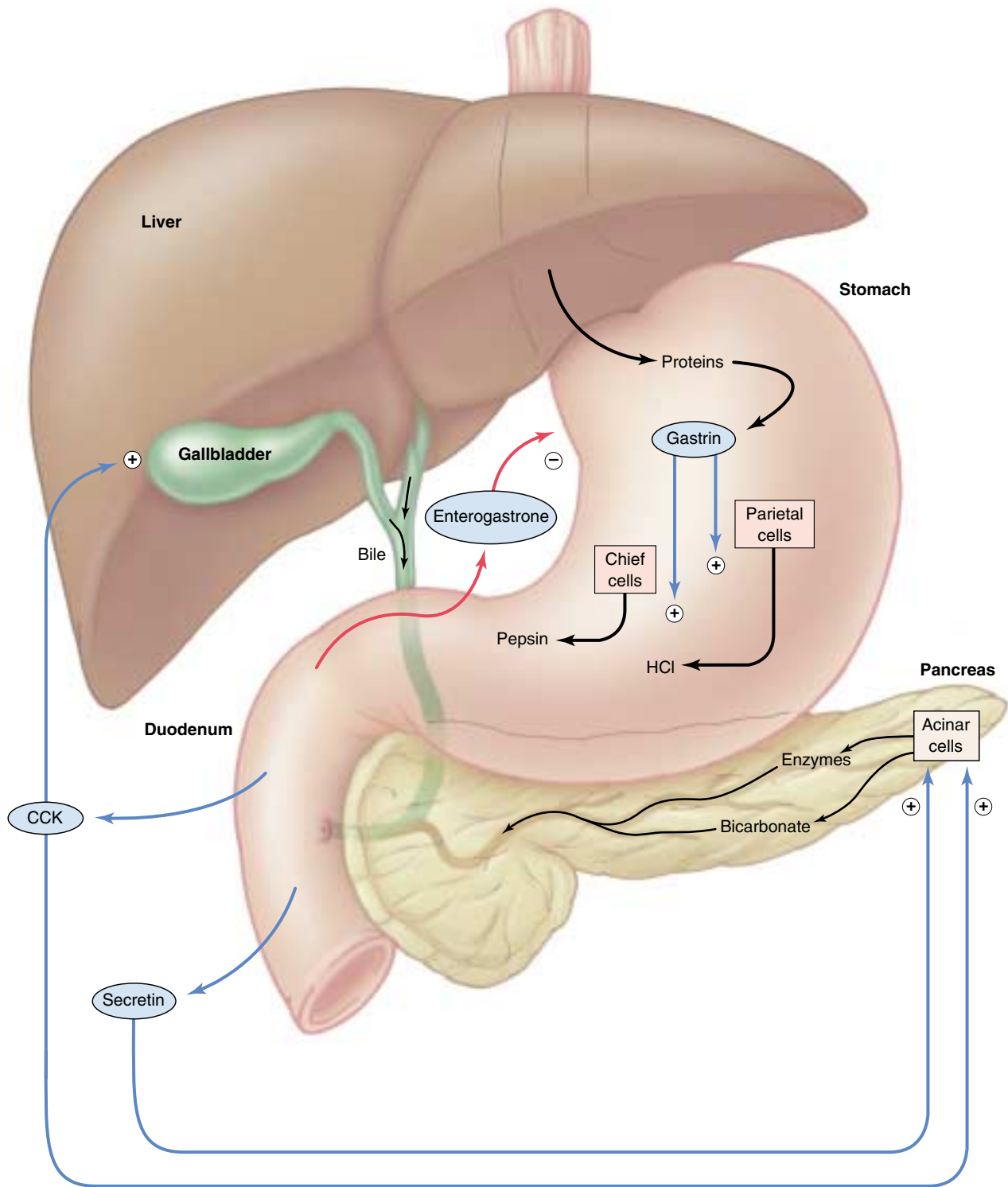


FIGURE 51.21

Hormonal control of the gastrointestinal tract. Gastrin is secreted by the mucosa of the stomach and stimulates the secretion of pepsinogen (which is converted into pepsin) and HCl. The duodenum secretes three hormones: cholecystokinin (CCK), which stimulates contraction of the gallbladder and secretion of pancreatic enzymes; secretin, which stimulates secretion of pancreatic bicarbonate; and an enterogastrone, which inhibits stomach emptying.

51.5 All animals require food energy and essential nutrients.

Food Energy and Energy Expenditure

The ingestion of food serves two primary functions: it provides a source of energy, and it provides raw materials the animal is unable to manufacture for itself. Even an animal that is completely at rest requires energy to support its metabolism; the minimum rate of energy consumption under defined resting conditions is called the basal metabolic rate (BMR). The BMR is relatively constant for a given individual, depending primarily on the person's age, sex, and body size.

Exercise raises the metabolic rate above the basal levels, so the amount of energy that the body consumes per day is determined not only by the BMR but also by the level of physical activity. If food energy taken in is greater than the energy consumed per day, the excess energy will be stored in glycogen and fat. Because glycogen reserves are limited, however, continued ingestion of excess food energy results primarily in the accumulation of fat. The intake of food energy is measured in kilocalories (1 kilocalorie = 1000 calories; nutritionists use Calorie with a capital C instead of kilocalorie). The measurement of kilocalories in food is determined by the amount of heat generated when the food is "burned," either literally, or when the caloric content of food is measured using a calorimeter, or in the body when the food is digested. Caloric intake can be altered by the choice of diet, and the amount of energy expended in exercise can be changed by the choice of lifestyle. The daily energy expenditures (metabolic rates) of people vary between 1300 and 5000 kilocalories per day, depending on the person's BMR and level of physical activity. If the food kilocalories ingested exceed the metabolic rate for a sustained period, the person will accumulate an amount of fat that is deleterious to health, a condition called **obesity**. In the United States, about 30% of middle-aged women and 15% of middle-aged men are classified as obese, which means they weigh at least 20% more than the average weight for their height.

Regulation of Food Intake

Scientists have for years suspected that adipose tissue secretes a hormonal *satiety factor* (a circulating chemical that decreases appetite), because genetically obese mice lose weight when their circulatory systems are surgically joined with those of normal mice. Apparently, some weight-loss hormone was passing into the obese mice! The satiety factor secreted by adipose tissue has recently been identified. It is the product of a gene first observed in a strain of mice known as *ob/ob* (*ob* stands for "obese"; the double symbols indicate that the mice are homozygous for this gene—they inherit it from both parents). The *ob* gene has been cloned in mice, and more recently



FIGURE 51.22
Injection of the hormone leptin causes genetically obese mice to lose weight. These two mice are identical twins, both members of a mutant strain of obese mice. The mouse on the right has been injected with the hormone leptin. It lost 30% of its body weight in just two weeks, with no apparent side effects.

in humans, and has been found to be expressed (that is, to produce mRNA) only in adipocytes. The protein product of this gene, the presumed satiety factor, is called leptin. The *ob* mice produce a mutated and ineffective form of leptin, and it is this defect that causes their obesity. When injected with normal leptin, they stop eating and lose weight (figure 51.22).

More recent studies in humans show that the activity of the *ob* gene and the blood concentrations of leptin are actually higher in obese than in lean people, and that the leptin produced by obese people appears to be normal. It has therefore been suggested that most cases of human obesity may result from a reduced sensitivity to the actions of leptin in the brain rather than from reduced leptin production by adipose cells. Aggressive research is ongoing, as might be expected from the possible medical and commercial applications of these findings.

In the United States, serious eating disorders have become much more common since the mid-1970s. The most common of these disorders are *anorexia nervosa*, a condition in which the afflicted individuals literally starve themselves, and *bulimia*, in which individuals gorge themselves and then vomit, so that their weight stays constant. Ninety to 95% of those suffering from these disorders are female; researchers estimate that 2 to 5% of the adolescent girls and young women in the United States have eating disorders.

The amount of caloric energy expended by the body depends on the basal metabolic rate and the additional calories consumed by exercise. Obesity results if the ingested food energy exceeds the energy expenditure by the body over a prolonged period.

Essential Nutrients

Over the course of their evolution, many animals have lost the ability to synthesize specific substances that nevertheless continue to play critical roles in their metabolism. Substances that an animal cannot manufacture for itself but which are necessary for its health must be obtained in the diet and are referred to as **essential nutrients**.

Included among the essential nutrients are *vitamins*, certain organic substances required in trace amounts. Humans, apes, monkeys, and guinea pigs, for example, have lost the ability to synthesize ascorbic acid (vitamin C). If vitamin C is not supplied in sufficient quantities in their diets, they will develop scurvy, a potentially fatal disease. Humans require at least 13 different vitamins (table 51.3).

Some essential nutrients are required in more than trace amounts. Many vertebrates, for example, are unable to synthesize 1 or more of the 20 amino acids used in making proteins. These *essential amino acids* must be obtained from proteins in the food they eat. There are nine essential amino acids for humans. People who are vegetarians must

choose their foods so that the essential amino acids in one food complement those in another.

In addition, all vertebrates have lost the ability to synthesize certain unsaturated fatty acids and therefore must obtain them in food. On the other hand, some essential nutrients that vertebrates can synthesize cannot be manufactured by the members of other animal groups. For example, vertebrates can synthesize cholesterol, a key component of steroid hormones, but some carnivorous insects cannot.

Food also supplies **essential minerals** such as calcium, phosphorus, and other inorganic substances, including a wide variety of *trace elements* such as zinc and molybdenum which are required in very small amounts (see table 2.1). Animals obtain trace elements either directly from plants or from animals that have eaten plants.

The body requires vitamins and minerals obtained in food. Also, food must provide particular essential amino acids and fatty acids that the body cannot manufacture by itself.

Table 51.3 Major Vitamins

Vitamin	Function	Source	Deficiency Symptoms
Vitamin A (retinol)	Used in making visual pigments, maintenance of epithelial tissues	Green vegetables, milk products, liver	Night blindness, flaky skin
B-complex vitamins			
B ₁	Coenzyme in CO ₂ removal during cellular respiration	Meat, grains, legumes	Beriberi, weakening of heart, edema
B ₂ (riboflavin)	Part of coenzymes FAD and FMN, which play metabolic roles	Many different kinds of foods	Inflammation and breakdown of skin, eye irritation
B ₃ (niacin)	Part of coenzymes NAD ⁺ and NADP ⁺	Liver, lean meats, grains	Pellagra, inflammation of nerves, mental disorders
B ₅ (pantothenic acid)	Part of coenzyme-A, a key connection between carbohydrate and fat metabolism	Many different kinds of foods	Rare: fatigue, loss of coordination
B ₆ (pyridoxine)	Coenzyme in many phases of amino acid metabolism	Cereals, vegetables, meats	Anemia, convulsions, irritability
B ₁₂ (cyanocobalamin)	Coenzyme in the production of nucleic acids	Red meats, dairy products	Pernicious anemia
Biotin	Coenzyme in fat synthesis and amino acid metabolism	Meat, vegetables	Rare: depression, nausea
Folic acid	Coenzyme in amino acid and nucleic acid metabolism	Green vegetables	Anemia, diarrhea
Vitamin C	Important in forming collagen, cement of bone, teeth, connective tissue of blood vessels; may help maintain resistance to infection	Fruit, green leafy vegetables	Scurvy, breakdown of skin, blood vessels
Vitamin D (calciferol)	Increases absorption of calcium and promotes bone formation	Dairy products, cod liver oil	Rickets, bone deformities
Vitamin E (tocopherol)	Protects fatty acids and cell membranes from oxidation	Margarine, seeds, green leafy vegetables	Rare
Vitamin K	Essential to blood clotting	Green leafy vegetables	Severe bleeding

**Summary****Questions****Media Resources****51.1 Animals employ a digestive system to prepare food for assimilation by cells.**

- The digestive system of vertebrates consists of a gastrointestinal tract and accessory digestive organs.
- Different regions of the digestive tract display specializations of structure and function.

1. What are the layers that make up the wall of the vertebrate gastrointestinal tract? What type of tissue is found in each layer?



- Art Activity: Digestive tract wall



- Introduction to digestion
- Human digestion
- Digestion overview

51.2 Food is ingested, swallowed, and transported to the stomach.

- The teeth of carnivores are different from those of herbivores
- The esophagus contracts in peristaltic waves to drive the swallowed food to the stomach.
- Cells of the gastric mucosa secrete hydrochloric acid, which activates pepsin, an enzyme that promotes the partial hydrolysis of ingested proteins.

2. How does tooth structure vary among carnivores, herbivores, and omnivores?

3. What normally prevents regurgitation in humans, and why can't horses regurgitate?

4. What inorganic substance is secreted by parietal cells?



- Art Activities: Digestive system
Mouth
Teeth
Swallowing
Glottis function

51.3 The small and large intestines have very different functions.

- The duodenum receives pancreatic juice and bile, which help digest the chyme that arrives from the stomach through the pyloric valve.
- Digestive enzymes in the small intestine finish the breakdown of food into molecules that can be absorbed by the small intestine.
- The large intestine absorbs water and ions, as well as certain organic molecules such as vitamin K; the remaining material passes out of the anus.

5. How are the products of protein and carbohydrate digestion absorbed across the intestinal wall, and where do they go after they are absorbed?

6. What anatomical and behavioral specializations do ruminants have for making use of microorganisms?



- Art Activities: Small intestine anatomy
Hepatic lobules



- Stomach to small intestine
- Small intestine digestion

51.4 Accessory organs, neural stimulation, and endocrine secretions assist in digestion.

- Pancreatic juice contains bicarbonate to neutralize the acid chyme from the stomach. Bile contains bile pigment and bile salts, which emulsify fat. The liver metabolizes toxins and hormones that are delivered to it in the hepatic portal vein; the liver also helps to regulate the blood glucose concentration.
- The stomach secretes the hormone gastrin, and the small intestine secretes various hormones that help to regulate the digestive system.

7. What are the main exocrine secretions of the pancreas, and what are their functions?

8. What is the function of bile salts in digestion?

9. Describe the role of gastrin and secretin in digestion.



- Art Activity: Digestive system



- formation of gallstones

51.5 All animals require food energy and essential nutrients.

- The basal metabolic rate (BMR) is the lowest level of energy consumption of the body.
- Vitamins, minerals, and the essential amino acids and fatty acids must be supplied in the diet.

10. What is a vitamin? What is the difference between an essential amino acid and any other amino acid?



- Nutrition