numerous health problems can occur, particularly in regard to these systems. One condition that is common in very premature babies (those born at 32 weeks or earlier) is respiratory distress syndrome (RDS). Because the lungs of a fetus do not normally function until full term (40 weeks), lung development is not complete when a baby is born prematurely. Usually, a natural surfactant that helps keep the air sacs of the lungs inflated so that gas exchange can occur is not being produced. Without treatment, RDS is often fatal because the blood is not being oxygenated. Now, an artificial surfactant is available, and premature babies are given the surfactant they lack. This treatment greatly increases the likelihood that premature babies will survive. Other medical breakthroughs are also now available to encourage the functioning of a premature baby's organ systems.

The maintenance systems have vital roles in the overall functioning of the body, and a malfunction in one of these systems can lead to problems in other systems. In this chapter, you will learn about the structure and function of the digestive, respiratory, and urinary systems, and how they support the body's other organ systems.

24.1 Digestive System

The cells of your body are bathed in tissue fluid. They acquire oxygen and nutrients and get rid of carbon dioxide and other wastes through exchanges with tissue fluid. In turn, tissue fluid makes these same exchanges with the blood. Blood is refreshed because the digestive, respiratory, and urinary systems make exchanges with the external environment. Only in this way is blood supplied with the oxygen and nutrients cells require and cleansed of waste molecules. In this first section, we consider how the digestive system contributes to homeostasis (Fig. 24.1).

Tube-Within-a-Tube Body Plan

Hydra and planarians (see Fig. 23.1) have a sac body plan—that is, the mouth, like the top of a sack, serves as both an entrance and an exit. Most other animals, such as the earthworm, have a tube-within-a-tube plan, so called because the inner tube has both an entrance and an exit—the mouth and the anus. Therefore, it is called a complete digestive tract (Fig. 24.2*a*). Notice that the inner tube (the digestive tract, sometimes called the alimentary canal) is separated from the outer tube (the body wall) by the **coelom.** The digestive tract of humans and other vertebrates consists of so many specialized organs that it might be hard to realize that the basic plan of vertebrates is the same as that of the earthworm (Fig. 24.2*b*). The digestive tract of humans exemplifies that the tube-within-a-tube plan and a complete tract result in specialization of parts.

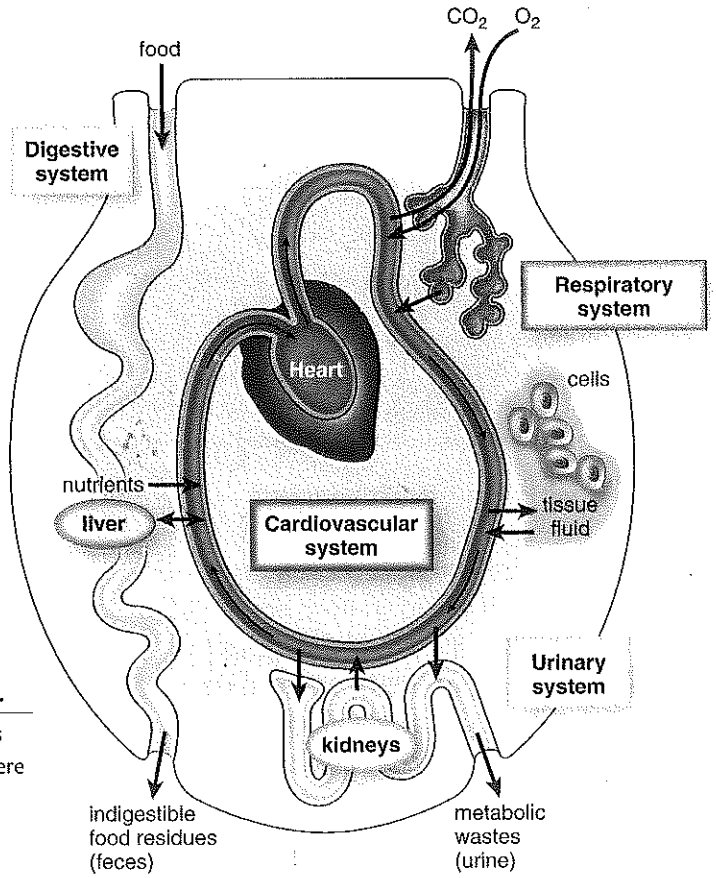
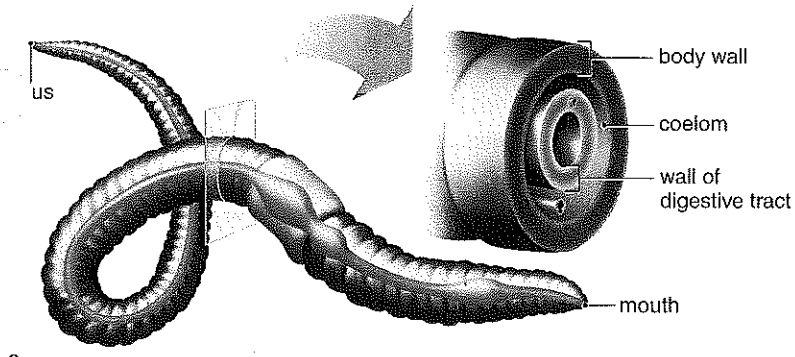
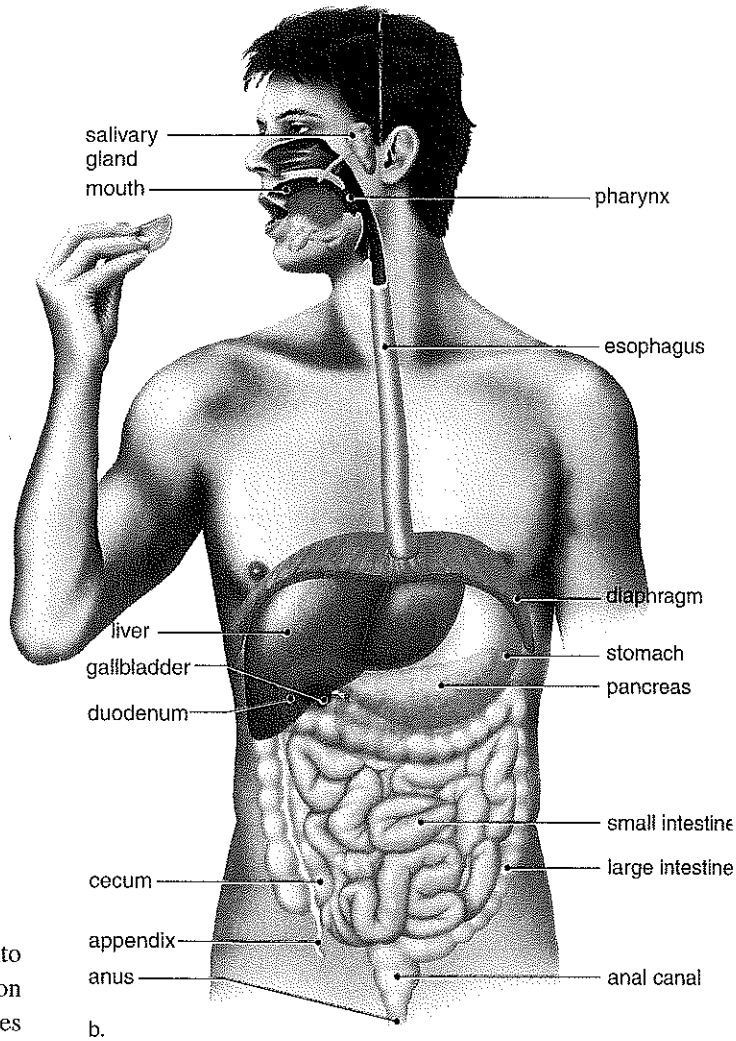


Figure 24.1 Keeping the internal environment steady.

The digestive system takes in food and digests it to nutrient molecules that enter the blood. The blood transports nutrients to the tissues where exchange occurs with tissue fluid. Later in this chapter we will also consider the manner in which the respiratory system and the urinary system help keep the internal environment relatively constant.



a.



b.

Figure 24.2 **Complete digestive system.**

The earthworm (**a**) and humans (**b**) have complete digestive systems. A complete digestive system leads to specialization of organs along the digestive tract.

Digestion of food in earthworms and humans is an extracellular process. Digestive enzymes, produced by glands in the wall of the tract or by accessory glands that lie nearby, enter the tract. Food is never found within these accessory glands, only within the tract itself.

Digestion contributes to homeostasis by providing the body's cells with the nutrients they need to continue living. A digestive tract performs the following functions:

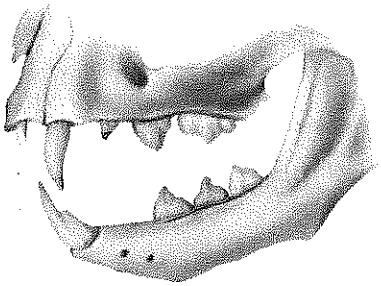
1. Ingests food.
2. Breaks food down into small molecules that can cross plasma membranes.
3. Absorbs nutrient molecules.
4. Eliminates indigestible remains.

Mouth

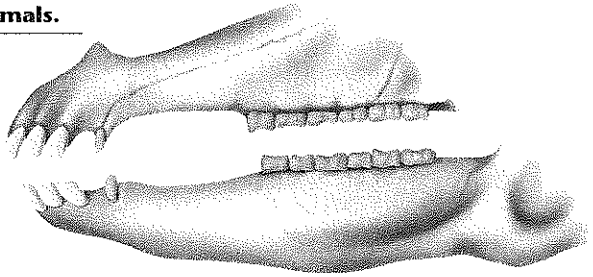
In humans, the digestive system begins with the **mouth,** which chews food into pieces convenient for swallowing. Many vertebrates have teeth, an exception being birds, which lack teeth and depend on the churning of small pebbles within a gizzard to break up their food. The teeth (dentition) of mammals reflect their diet (Fig. 24.3). **Carnivores** eat meat, which is easily digestible because the cells don't have a cellulose wall. **Herbivores** eat plant material, which needs a lot of chewing and other processing to break up the cellulose walls. Humans are **omnivores;** they eat both meat and plant material. The four front teeth (top and bottom) of humans are sharp, chisel-shaped incisors used for biting. On each side of the incisors are the sharp, pointed canines used for tearing food. The premolars and molars grind and crush food. It is as though humans are carnivores in the front of their mouths and herbivores in the back.

Key:
incisors
canines
premolars
molars

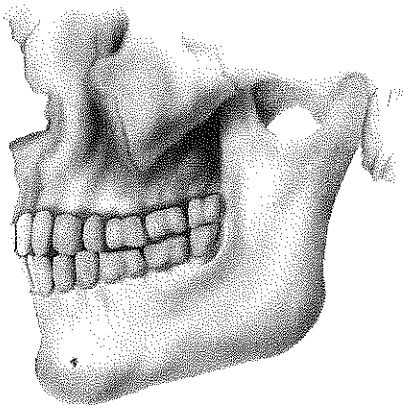
Figure 24.3 **Dentition among mammals.**



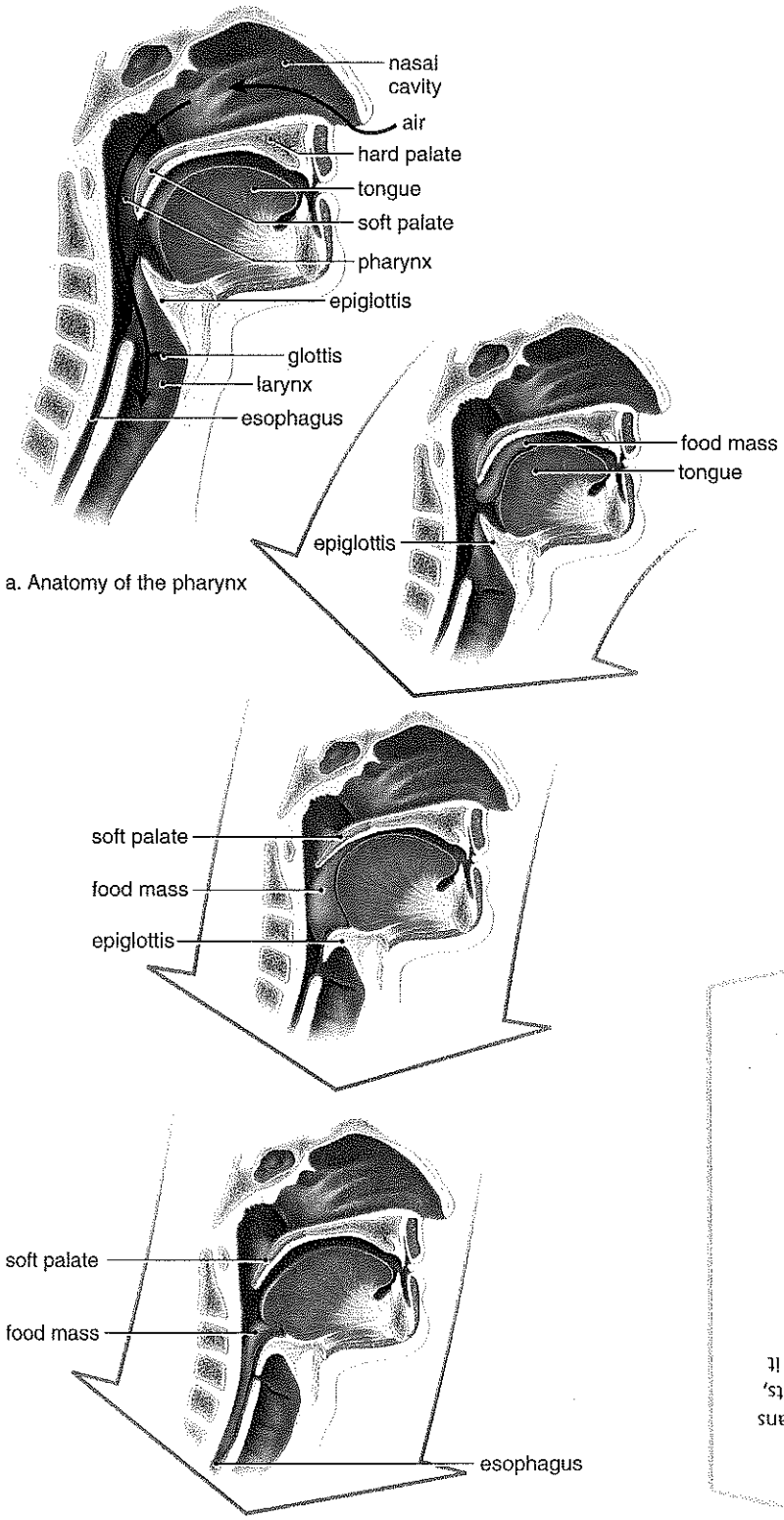
a. Carnivores have pointed incisors and enlarged canine teeth for biting and tearing.



b. Herbivores have large, flat premolars and molars for grinding.



c. The front teeth of humans are like those of carnivores, and the back teeth are like those of herbivores.



jure 24.4 The human mouth, pharynx, esophagus, and larynx.

a. The palates (both hard and soft) separate the mouth from the nasal cavities. The pharynx leads to the esophagus and the larynx. **b.** When food is swallowed, the soft palate closes off the nasal cavities, and the epiglottis closes off the larynx.

Food contains cells composed of molecules of carbohydrates, proteins, nucleic acids, and lipids. During digestion, hydrolytic enzymes break down these large molecules to smaller molecules. The process begins in the mouth. Three pairs of **salivary glands** send saliva by way of ducts to the mouth. Saliva contains the enzyme **salivary amylase,** which breaks down starch, a carbohydrate, to maltose, a disaccharide. While in the mouth, food is manipulated by a muscular tongue, which has touch and pressure receptors similar to those in the skin. Taste buds that allow us to "taste" our food are also on the tongue as well as on the surface of the mouth. The tongue mixes the chewed food with saliva and then forms this mixture into a mass called a **bolus** that is swallowed.

Swallowing

The human digestive and respiratory passages come together in the **pharynx** and then separate (Fig. 24.4*a*). When food is swallowed, the soft palate, the rear portion of the mouth's roof, moves back to close off the nasal cavities (Fig. 24.4*b*). A flap of tissue called the **epiglottis** covers the glottis, an opening into the larynx. Now the bolus must move through the pharynx into the esophagus because the air passages are blocked.

The **esophagus** is a tubular structure that takes food to the stomach, which lies below the **diaphragm,** a muscular, membranous partition that divides the **thoracic** (upper) **cavity** from the **abdominal** (lower) **cavity** of the body. When food enters the esophagus, peristalsis begins. **Peristalsis** is a rhythmic contraction that moves the contents along in tubular organs—in this case, those of the digestive tract.

Check Your Progress

1. List the three organ systems that make exchanges with the external environment and blood.
2. Compare and contrast the human digestive system with that of an earthworm.
3. List the functions of a digestive tract.
4. Explain why carnivores do not need teeth for grinding food.
5. Describe the function of peristalsis in digestion.

Answers: 1. Digestive, respiratory, and urinary systems. 2. Both are tube-within-a-tube plans, but the human system has many more specialized organs than that of an earthworm. 3. Ingest and break down food, absorb nutrients, and eliminate indigestible material. 4. Meat is easy to break down because it does not contain cellulose, so extensive chewing is not necessary. 5. Peristalsis moves materials through the digestive tract.

omach

The human **stomach** is a thick-walled, J-shaped organ that stretches and stores food (Fig. 24.5). It also begins the digestion of proteins, and regulates the entrance of food into the small intestine.

The wall of the stomach has deep folds, which disappear as the stomach fills to an approximate capacity of 1 liter. Therefore, humans can periodically eat relatively large meals and spend the rest of their time at other activities. But the stomach is much more than a mere storage organ, as was discovered by William Beaumont in the mid-nineteenth century. Beaumont, an American doctor, had a French Canadian patient, Alexis St. Martin, who had been shot in the stomach. When the wound healed, St. Martin was left with an opening that allowed Beaumont to look inside the stomach and to collect gastric (stomach) juices produced by gastric glands. Beaumont was able to determine that the muscular walls of the stomach contract vigorously and mix food with juices that are secreted whenever food enters the stomach. He found that gastric juice contains hydrochloric acid (HCl) and a substance, now called pepsin, that is active in digestion.

We now know that the epithelial lining of the stomach, called a mucosa, has millions of gastric glands. These gastric glands produce gastric juice containing so much hydrochloric acid that the stomach routinely has a pH of about 2. Such high acidity is usually sufficient to kill any microbes that might be in food. This low pH also promotes the activity of **pepsin,** a hydrolytic enzyme that acts on protein to produce peptides. In addition, high ‹idity causes *heartburn* and *gastric reflux disease* when gastric juice backs ..p into the esophagus.

As with the rest of the digestive tract, a thick layer of mucus protects the wall of the stomach from enzymatic action. Still, an ulcer, which is an open sore in the wall caused by the gradual destruction of tissues, may occur in some individuals. Ulcers are due to an infection by an acid-resistant bacterium, *Helicobacter pylori,* which is able to attach to the epithelial lining. Wherever the bacterium attaches, the lining stops producing mucus, and the area becomes exposed to digestive action. Then an ulcer develops.

Peristalsis pushes food along in the stomach as it does in other digestive organs (Fig. 24.5*b*). At the base of the stomach is a narrow opening controlled by a *sphincter,* a muscle that surrounds a tube and closes or opens it by contracting and relaxing. Whenever this sphincter relaxes, a small quantity of material passes through the opening into the small intestine.

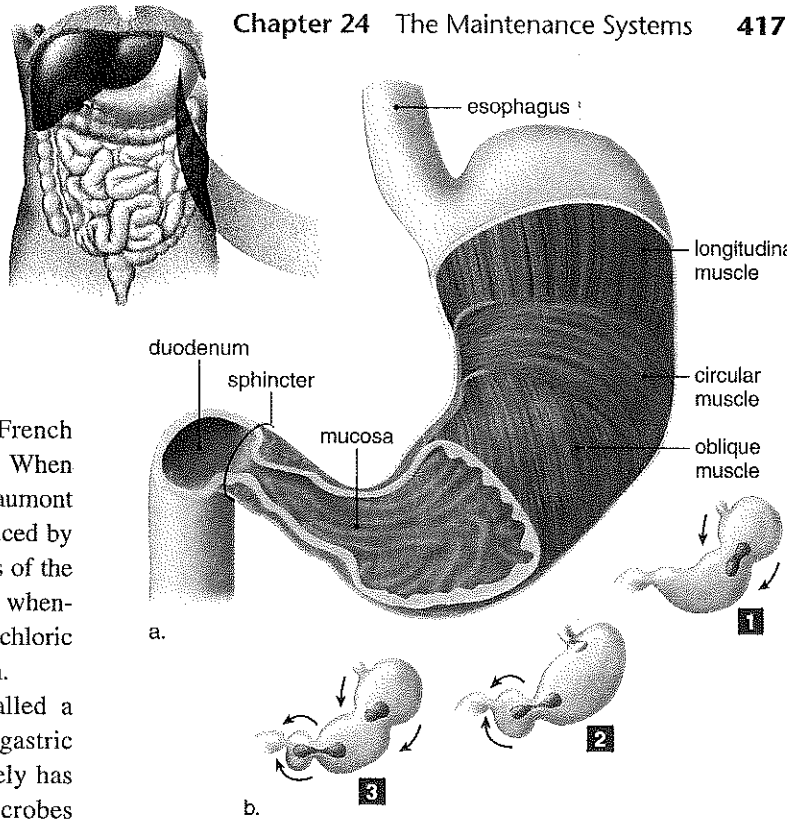


Figure 24.5 Anatomy of the human stomach.

a. The stomach has a thick wall that expands as it fills with food. The wall contains three layers of muscle, and their presence allows the stomach to churn and mix food with gastric juices. The mucosa of the stomach wall secretes mucus and contains gastric glands, which secrete gastric juices active in the digestion of protein. **b.** Peristalsis, a rhythmic contraction, occurs along the length of the digestive tract.

Ruminants Ruminants, a type of mammal that includes cattle, sheep, goats, deer, and buffalo, are named for a part of their stomachs, the rumen (Fig. 24.6). The rumen contains symbiotic bacteria and protozoans that, unlike the mammal, can digest cellulose. After these herbivores feed on grass, it goes to the rumen, where it is broken down and then formed into small balls of cud. The cud then returns to the mouth where the animal "chews the cud." The cud may return to the rumen for a second go-round before passing through the other chambers of the stomach. The ‹t chamber is analogous to the human stomach, being the place where protein . digested to peptides.

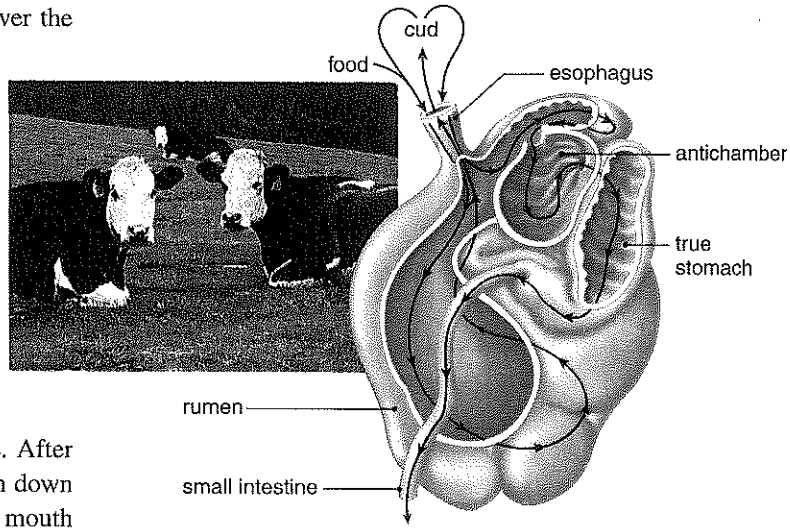


Figure 24.6 A ruminant's stomach.

Ruminants eat grass, which is made of cells with strong cellulose walls. The first chamber of a ruminant's stomach, called the rumen, contains symbiotic bacteria and protozoans that can digest cellulose. After a first pass through the rumen, the "cud" returns to the mouth where it is leisurely chewed. Then, it may return to the rumen for a second go-round of digestion before passing through to the true stomach.

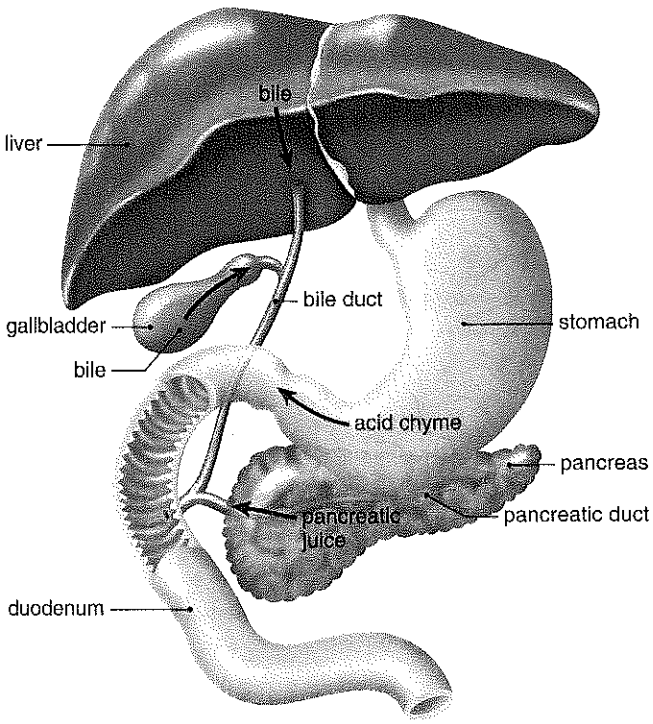


Figure 24.7 The pancreatic and bile ducts empty into the duodenum.

Bile, made by the liver and stored in the gallbladder, and pancreatic juice, which contains enzymes, enter the duodenum by way of ducts.

Small Intestine

Processing food in humans is more complicated than one might think. So far, the food has been chewed in the mouth and worked on by the enzyme salivary amylase, which digests starch to maltose. In addition, the digestion of protein has begun in the stomach as pepsin digests proteins to peptides. By now, the contents of the digestive tract are called **chyme.** Chyme passes from the stomach to the **small intestine,** a long, coiled tube that has two functions: (1) digestion of all the molecules in chyme, including polymers of carbohydrate, protein, nucleic acid, and fat, and (2) absorption of the nutrient molecules into the body.

The first part of the small intestine is called the duodenum. Two important accessory glands, the **liver,** the largest organ in the body, and the **pancreas,** located behind the stomach, send secretions to the duodenum by way of ducts (Fig. 24.7). The liver produces **bile,** which is stored in the **gallbladder.** Bile looks green because it contains pigments that are the products of hemoglobin breakdown. This green color is familiar to anyone who has observed how bruised tissue changes color. Hemoglobin within the bruise is breaking down into the same types of pigments found in bile. Bile also contains bile salts, which break up fat into fat droplets by a process called **emulsification.** Fat droplets mix with water and have more surface area for digestion by enzymes.

The pancreas produces pancreatic juice, which contains sodium bicarbonate ($NaHCO_3$) and digestive enzymes. $NaHCO_3$ neutralizes chyme and makes the pH of the small intestine slightly basic. The higher pH helps prevent autodigestion of the intestinal lining by pepsin and optimizes the pH for pancreatic enzymes. **Pancreatic amylase** digests starch to maltose; **trypsin** digests proteins to peptides; **lipase** digests fat droplets to glycerol and fatty acids; and **nuclease** digests nucleic acids to nucleotides.

Still more digestive enzymes are present in the small intestine. The wall of the small intestine contains fingerlike projections called **villi** (Fig. 24.8*b*). The epithelial cells of the villi produce **intestinal enzymes,** which remain attached to them. These enzymes complete the digestion of peptides and sugars. Peptides, which result from the first step in protein digestion, are digested by peptidase to amino acids. Maltose, which results from the first step in starch digestion, is digested by maltase to glucose. Other disaccharides, each of which is acted upon by a specific enzyme, are digested to simple sugars also.

Finally, these small nutrient molecules can be absorbed into the body. Our cells use these molecules as a source of energy and as building blocks to make their own macromolecules.

Absorption by Villi The wall of the small intestine is adapted to absorbing nutrient molecules because it has an extensive surface area—approximately that of a tennis court! First, the mucous membrane layer of the small intestine has circular folds that give it an almost corrugated appearance (Fig. 24.8*a*). Second, on the surface of these circular folds are the villi. Finally, the cells on the surface of the villi have minute projections called **microvilli** (Fig. 24.8*c*). If the human small intestine were simply a smooth tube, it would have to be 500 to 600 meters long to have a comparable surface area for absorption. Carnivores have a much shorter digestive tract than herbivores because meat is easier to process than plant material (Fig. 24.9).

The villi of the small intestine absorb small nutrient molecules into the body. Each villus contains an extensive network of blood capillaries and a lymphatic capillary called a **lacteal.**

Check Your Progress

1. Describe the functions of the stomach.
2. Describe the relationship between the duodenum and the liver and pancreas.

Answers: 1. The stomach stores food and continues digestion, kills microbes, and moves partially digested material into the intestines. 2. The liver and pancreas secrete bile and pancreatic juice, respectively, into the duodenum.

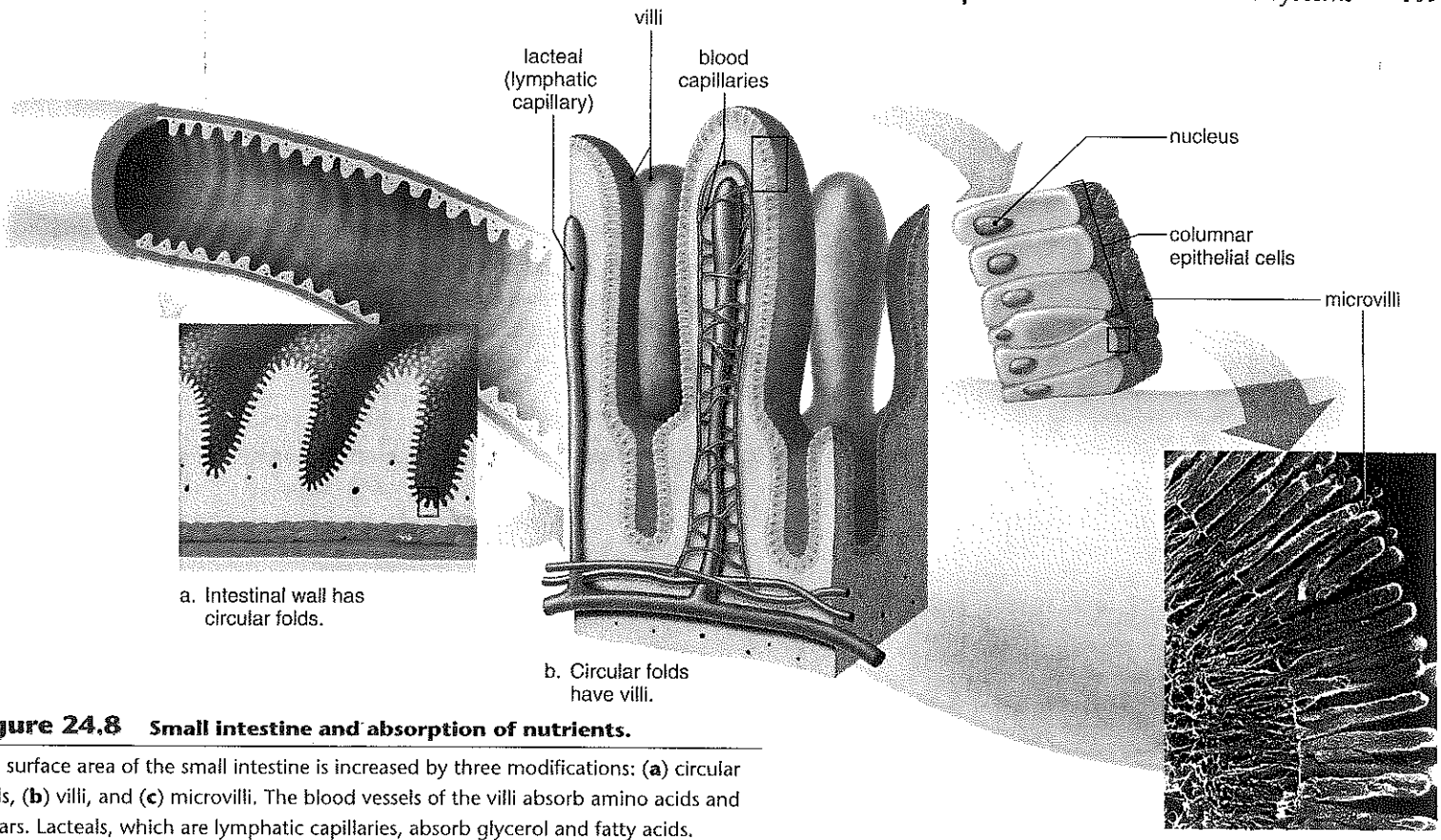


Figure 24.8 Small intestine and absorption of nutrients.

The surface area of the small intestine is increased by three modifications: (**a**) circular folds, (**b**) villi, and (**c**) microvilli. The blood vessels of the villi absorb amino acids and sugars. Lacteals, which are lymphatic capillaries, absorb glycerol and fatty acids.

As discussed in Chapter 23, the lymphatic system is an adjunct to the cardiovascular system—its vessels carry a fluid called lymph to the cardiovascular veins. Sugars and amino acids enter the blood capillaries of a villus. In contrast, glycerol and fatty acids (digested from fats) enter the epithelial cells of the villi, and within them are joined and packaged as lipoprotein droplets, which enter a lacteal. Absorption continues until almost all nutrient molecules have been absorbed. Absorption occurs by diffusion, as well as by active transport, which requires an expenditure of cellular energy. Lymphatic vessels transport lymph to cardiovascular veins. Eventually, the bloodstream carries the nutrients absorbed by the digestive system to all the cells of the body.

Large Intestine

The word *bowel* technically means the part of the digestive tract between the stomach and the anus, but it is sometimes used to mean only the large intestine. The **large intestine** absorbs water, salts, and some vitamins. It also stores indigestible material until it is eliminated at the anus. The large intestine takes its name from its diameter rather than its length, which is shorter than that of the small intestine. The large intestine has a blind pouch below the entry of the small intestine with a small projection called the **appendix.** In humans, the appendix may play a role in fighting infections. In the condition called *appendicitis,* the appendix becomes infected and so filled with fluid that

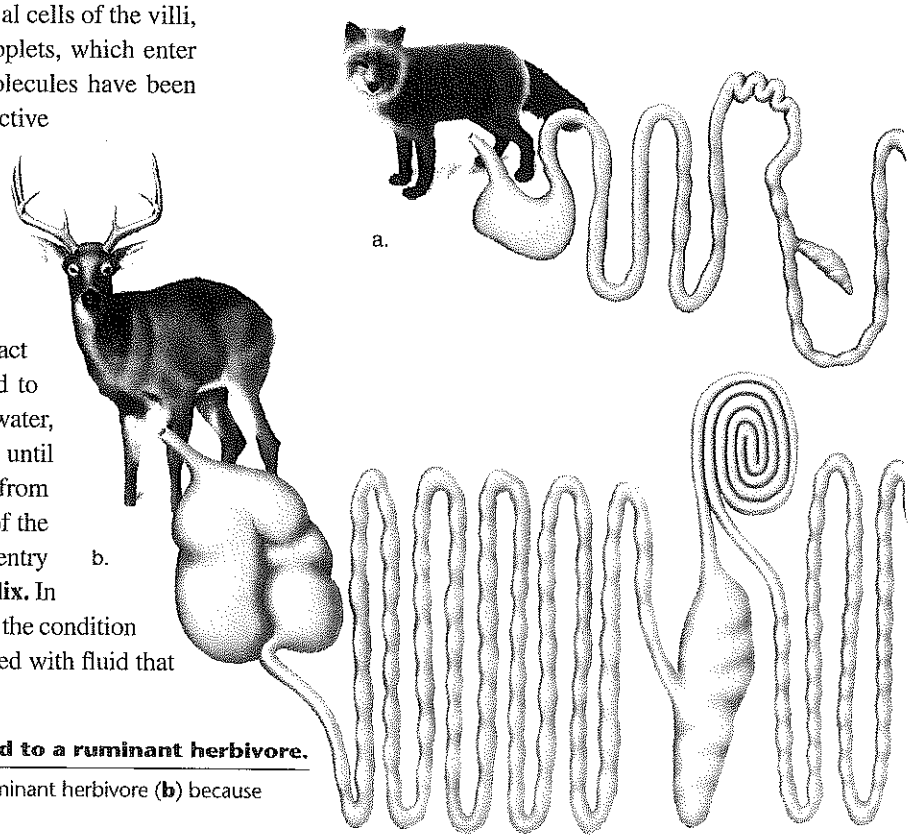


Figure 24.9 Digestive tract of a carnivore compared to a ruminant herbivore.

The digestive tract of a carnivore (**a**) is much shorter than that of a ruminant herbivore (**b**) because proteins can be more easily digested than plant matter.

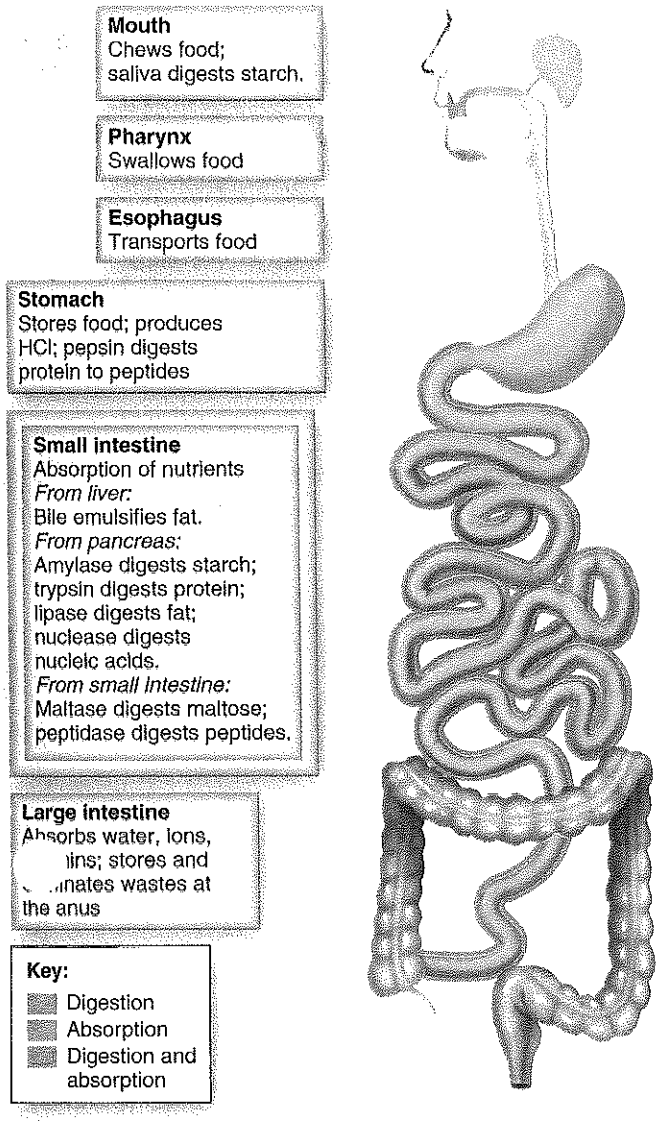


Figure 24.10 The digestive organs and their functions.

A review of the processing of food to nutrient molecules and their absorption into the body.

it may burst. If an infected appendix bursts before it can be removed, a serious, generalized infection of the abdominal lining, called peritonitis, may result.

About 1.5 liters of water enter the digestive tract daily as a result of eating and drinking. An additional 8.5 liters also enter the digestive tract each day, carrying the various substances secreted by the digestive glands. About 95% of this water is absorbed by the small intestine, and much of the remaining portion is absorbed by the large intestine. If this water is not reabsorbed, **diarrhea** can occur, leading to serious dehydration and ion loss, especially in children.

The large intestine has a large population of bacteria, notably *Escherichia coli.* The bacteria break down indigestible material, and they also produce some vitamins, including vitamin K. Vitamin K is necessary for blood clotting. Digestive wastes (feces) eventually leave the body through the **anus,** the opening of the anal canal. Feces are about 75% water and 25% solid matter. Almost one-third of this solid matter is made up of intestinal bacteria. The remainder is indigestible plant material (also called fiber), fats, waste products (such as bile pigments), inorganic material, mucus, and dead cells from the intestinal lining. A diet that includes fiber adds bulk to the feces, improves regularity of elimination, and prevents *constipation.*

The large intestine (also called the colon) is subject to the development of **polyps,** which are small growths arising from the mucosa. Polyps, whether they are benign or cancerous, can be removed surgically.

Figure 24.10 reviews the digestive process.

Check Your Progress

Contrast the functions of the small intestine and the large intestine.

Answer: The small intestine digests all types of food, and it produces enzymes that complete the breakdown of food to small molecules that can be absorbed across its villi. No digestion occurs in the large intestine, but it does store digestive remains until they are eliminated. The large intestine also absorbs water, salts, and some vitamins.

Accessory Organs

The pancreas and the liver are accessory organs of digestion, along with the teeth, salivary glands, and gallbladder.

Pancreas

The pancreas (see Fig. 24.7) functions as both an endocrine gland and an exocrine gland. **Endocrine glands** are ductless and secrete their products into the blood. The pancreas is an endocrine gland when it produces and secretes the hormones **insulin** and **glucagon** into the bloodstream. **Exocrine glands** secrete into ducts. The pancreas is an exocrine gland when it produces and secretes pancreatic juice into the **duodenum** through the common bile duct.

Liver

The liver has numerous functions, including the following:

1. Detoxifies the blood by removing and metabolizing poisonous substances.

. Produces the plasma proteins, such as albumin and fibrinogen.
3. Destroys old red blood cells and converts hemoglobin to the breakdown products in bile (bilirubin and biliverdin).
4. Produces bile, which is stored in the gallbladder before entering the small intestine, where it emulsifies fats.
5. Stores glucose as glycogen and breaks down glycogen to glucose between meals to maintain a constant glucose concentration in the blood.
6. Produces urea from amino groups and ammonia.

Blood vessels from the large and small intestines merge to form the hepatic portal vein, which leads to the liver (Fig. 24.11). The liver helps maintain the glucose concentration in blood at about 0.1% by removing excess glucose from the hepatic portal vein and storing it as glycogen. Between meals, glycogen is broken down to glucose, and glucose enters the hepatic veins. Like plant-made starch, glycogen is made up of glucose molecules, and thus it is sometimes called animal starch. If the supply of glycogen and glucose runs short, the liver converts amino acids to glucose molecules.

Amino acids contain nitrogen in the form of amino groups, whereas glucose contains only carbon, oxygen, and hydrogen. Therefore, before amino acids can be converted to glucose molecules, deamination, the removal of amino groups from amino acids, must occur. By a complex metabolic pathway, the liver converts the amino groups to urea, the most common nitrogenous (nitrogen-containing) waste product of humans. After urea is formed in the liver, it is transported by the bloodstream to the kidneys, where it is excreted.

.er Disorders When a person is jaundiced, the skin has a yellowish tint due to an abnormally large quantity of bile pigments in the blood. In hemolytic jaundice, red blood cells are broken down in abnormally large amounts; in obstructive jaundice, the bile duct is obstructed, or the liver cells are damaged. Obstructive jaundice often occurs when crystals of cholesterol precipitate out of bile and form gallstones.

Jaundice can also result from viral infection of the liver, called *hepatitis*. Hepatitis A is most often caused by eating contaminated food. Hepatitis B and C are commonly spread by blood transfusions, kidney dialysis, and injection with unsterilized needles. These three types of hepatitis can also be spread by sexual contact.

Cirrhosis is a chronic liver disease in which the organ first becomes fatty, and later liver tissue is replaced by inactive fibrous scar tissue. Alcoholics often get cirrhosis, most likely due at least in part to the excessive amounts of alcohol the liver is forced to break down.

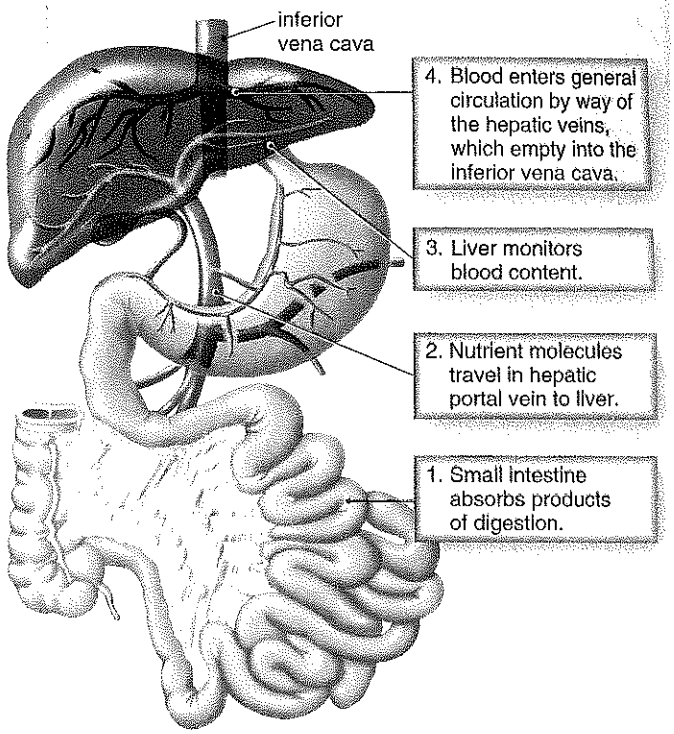


Figure 24.11 Hepatic portal system.

The hepatic portal vein takes the products of digestion from the digestive system to the liver, where they are processed before entering hepatic veins.

Regulation of Digestive Juices

Does your mouth water when you smell food cooking? Even the thought of food can sometimes cause the nervous system to order the secretion of digestive juices. The secretion of these juices is also under the influence of several peptide hormones, so called because each is a small sequence of amino acids. When ...ou eat a meal rich in protein, the stomach wall produces a pep- ... hormone that enters the bloodstream and doubles back to cause the stomach to produce more gastric juices. When protein and fat are present in the small intestine, another peptide hormone made in the intestinal wall stimulates the secretion of bile and pancreatic juices. In this way, the organs of digestion regulate their own needs.

Check Your Progress

List the functions of the liver.

Answer: The liver detoxifies the blood, produces plasma proteins, produces bile, stores glucose as glycogen, and produces urea.