Secretion of Bile

The liver secretes bile continuously, but bile secretion is increased by a meal. When bile arrives in the duodenum during a meal, the liver is stimulated to secrete more bile by the bile acids that return to the liver from the intestine via the hepatic portal vein (the enterohepatic circulation; see fig. 18.21). Endocrine and neural reflexes are also involved. Secretin stimulates the bile duct cells of the liver to secrete bicarbonate into the bile (leading to increased bile volume), and CCK enhances this effect. The secretion of CCK in response to fat in the chyme stimulates contractions of the gallbladder, allowing more bile to enter the duodenum. The bile then emulsifies the fat, aiding its digestion. Also, the arrival of chyme in the duodenum produces a neural reflex that stimulates contractions of the gallbladder.

Case Investigation CLUES

Alan's pain below his right scapula was triggered by eating peanut butter or bacon, but not by eating foods such as skinned chicken or fish.

- What component of the food was responsible for the painful reaction?
- How does this component of the food result in Alan's pain?

Trophic Effects of Gastrointestinal Hormones

Patients with tumors of the stomach pylorus exhibit excessive acid secretion and hyperplasia (growth) of the gastric mucosa. Surgical removal of the pylorus reduces gastric secretion and prevents growth of the gastric mucosa. Patients with peptic ulcers are sometimes treated by vagotomy—cutting of the portion of the vagus nerve that innervates the stomach. Vagotomy also reduces acid secretion but has no effect on the gastric mucosa. These observations suggest that the hormone gastrin, secreted by the pyloric mucosa, may exert stimulatory, or *trophic,* effects on the gastric mucosa. The structure of the gastric mucosa, in other words, is dependent upon the effects of gastrin.

In the same way, the structure of the acinar (exocrine) cells of the pancreas is dependent upon the trophic effects of CCK. Perhaps this explains why the pancreas, as well as the GI tract, atrophies during starvation. Since neural reflexes appear to be capable of regulating digestion, perhaps the primary function of the GI hormones is trophic—that is, maintenance of the structure of their target organs.

✔ CHECKPOINT

21. Describe the positive and negative feedback mechanisms that operate during the gastric phase of HCl and pepsinogen secretion.
22. Describe the mechanisms involved in the intestinal phase of gastric regulation, and explain why a fatty meal takes longer to leave the stomach than a meal low in fat.
23. Explain the hormonal mechanisms involved in the production and release of pancreatic juice and bile.
24. Describe the enteric nervous system, and identify some of the short reflexes that regulate intestinal function.

18.7 DIGESTION AND ABSORPTION OF CARBOHYDRATES, LIPIDS, AND PROTEINS

Polysaccharides and polypeptides are hydrolyzed into their subunits, which are secreted into blood capillaries. Fat is emulsified by bile salts, hydrolyzed into fatty acids and monoglycerides, and absorbed into the intestinal epithelial cells. Once inside the cells, triglycerides are resynthesized, combined with proteins, and secreted into the lymphatic fluid.

LEARNING OUTCOMES

After studying this section, you should be able to:

- ✔ Describe the processes involved in the digestion and absorption of carbohydrates and proteins
- ✔ Describe the processes involved in the digestion, absorption, and transport of dietary lipids

The caloric (energy) value of food is derived mainly from its content of carbohydrates, lipids, and proteins. In the average American diet, carbohydrates account for approximately 50% of the total calories, protein accounts for 11% to 14%, and lipids make up the balance. These food molecules consist primarily of long combinations of subunits (monomers) that must be digested by hydrolysis reactions into free monomers before absorption can occur. The characteristics of the major digestive enzymes are summarized in table 18.7.

Table 18.7 | Characteristics of the Major Digestive Enzymes

Enzyme	Site of Action	Source	Substrate	Optimum pH	Product(s)
Salivary amylase	Mouth	Saliva	Starch	6.7	Maltose
Pepsin	Stomach	Gastric glands	Protein	1.6–2.4	Shorter polypeptides
Pancreatic amylase	Duodenum	Pancreatic juice	Starch	6.7–7.0	Maltose, maltriose, and oligosaccharides
Trypsin, chymotrypsin, carboxypeptidase	Small intestine	Pancreatic juice	Polypeptides	8.0	Amino acids, dipeptides, and tripeptides
Pancreatic lipase	Small intestine	Pancreatic juice	Triglycerides	8.0	Fatty acids and monoglycerides
Maltase	Small intestine	Brush border of epithelial cells	Maltose	5.0–7.0	Glucose
Sucrase	Small intestine	Brush border of epithelial cells	Sucrose	5.0–7.0	Glucose + fructose
Lactase	Small intestine	Brush border of epithelial cells	Lactose	5.8–6.2	Glucose + galactose
Aminopeptidase	Small intestine	Brush border of epithelial cells	Polypeptides	8.0	Amino acids, dipeptides, tripeptides

Digestion and Absorption of Carbohydrates

Most carbohydrates are ingested as starch, which is a long polysaccharide of glucose in the form of straight chains with occasional branchings. The most commonly ingested sugars are sucrose (table sugar, a disaccharide of glucose and fructose) and lactose (milk sugar, a disaccharide of glucose and galactose). The digestion of starch begins in the mouth with the action of **salivary amylase.** This enzyme cleaves some of the bonds between adjacent glucose molecules, but most people don't chew their food long enough for sufficient digestion to occur in the mouth. The digestive action of salivary amylase stops some time after the swallowed bolus enters the stomach because this enzyme is inactivated at the low pH of gastric juice.

The digestion of starch, therefore, occurs mainly in the duodenum as a result of the action of **pancreatic amylase.** This enzyme cleaves the straight chains of starch to produce the disaccharide *maltose* and the trisaccharide *maltriose.* Pancreatic amylase, however, cannot hydrolyze the bond between glucose molecules at the branch points in the starch. As a result, short, branched chains of glucose molecules, called *oligosaccharides,* are released together with maltose and maltriose by the activity of this enzyme (fig. 18.32).

Maltose, maltriose, and oligosaccharides are hydrolyzed to their monosaccharides by brush border enzymes located on the microvilli of the epithelial cells in the small intestine.

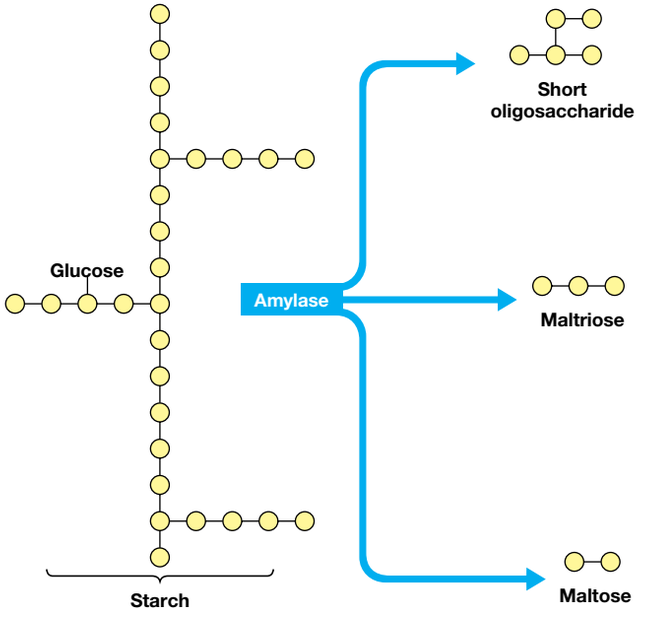


Figure 18.32 The action of pancreatic amylase. Pancreatic amylase digests starch into maltose, maltriose, and short oligosaccharides containing branch points in the chain of glucose molecules.

The brush border enzymes also hydrolyze the disaccharides sucrose and lactose into their component monosaccharides. These monosaccharides are then moved across the epithelial cell membrane by secondary active transport, in which the glucose shares a common membrane carrier with Na^+ (chapter 6; see fig. 6.20). There is also evidence that glucose may move passively (by facilitative diffusion) across the apical plasma membrane of the intestinal epithelium when the glucose concentration in the intestinal lumen is high (after a carbohydrate meal). Finally, glucose leaves the epithelial cells by facilitative diffusion and enters the interstitial fluid, from which it diffuses into nearby blood capillaries within the intestinal villi.

Digestion and Absorption of Proteins

Protein digestion begins in the stomach with the action of pepsin. Some amino acids are liberated in the stomach, but the major products of pepsin digestion are short-chain polypeptides. Pepsin digestion helps produce a more homogeneous chyme, but it is not essential for the complete digestion of protein that occurs—even in people with total gastrectomies—in the small intestine.

Most protein digestion occurs in the duodenum and jejunum. The pancreatic juice enzymes **trypsin, chymotrypsin,** and **elastase** cleave peptide bonds in the interior of the polypeptide chains. These enzymes are thus grouped together as *endopeptidases.* Enzymes that remove amino acids from the ends of polypeptide chains, by contrast, are *exopeptidases.* These include the pancreatic juice enzyme **carboxypeptidase,** which removes amino acids from the carboxyl-terminal end of polypeptide chains, and the brush border enzyme **aminopeptidase.** Aminopeptidase cleaves amino acids from the amino-terminal end of polypeptide chains.

As a result of the action of these enzymes, polypeptide chains are digested into free amino acids, dipeptides, and tripeptides. The free amino acids are absorbed by cotransport with Na^+ into the epithelial cells and secreted into blood capillaries. The dipeptides and tripeptides enter epithelial cells by the action of a single membrane carrier that has recently been characterized. This carrier functions in secondary active transport using a H^+ gradient to transport dipeptides and tripeptides into the cell cytoplasm. Within the cytoplasm, the dipeptides and tripeptides are hydrolyzed into free amino acids, which are then secreted into the blood (fig. 18.33).

Newborn babies appear to be capable of absorbing a substantial amount of undigested proteins (hence they can absorb some antibodies from their mother's first milk); in adults, however, only the free amino acids enter the portal vein. Foreign food protein, which would be very antigenic, does not normally enter the blood. An interesting exception is the protein toxin that causes botulism, produced by the bacterium *Clostridium botulinum.* This protein is resistant to digestion and is thus intact when it is absorbed into the blood.

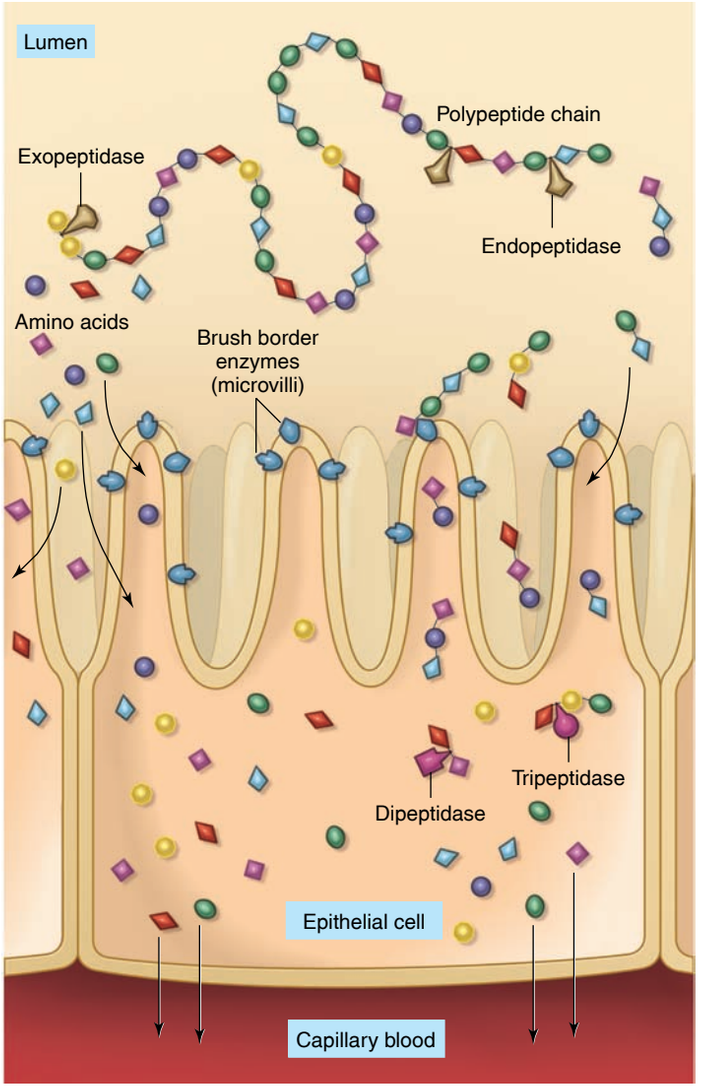


Figure 18.33 The digestion and absorption of proteins. Polypeptide chains of proteins are digested into free amino acids, peptides, and tripeptides by the action of pancreatic juice enzymes and brush border enzymes. The amino acids, dipeptides, and tripeptides enter duodenal epithelial cells. Dipeptides and tripeptides are hydrolyzed into free amino acids within the epithelial cells, and these products are secreted into interstitial fluid (not shown) and then into capillaries, which eventually drain into the hepatic portal vein.

Digestion and Absorption of Lipids

The salivary glands and stomach of neonates (newborns) produce lipases. In adults, however, very little lipid digestion occurs until the lipid globules in chyme arrive in the duodenum. Through mechanisms described next, the arrival of lipids (primarily triglyceride, or fat) in the duodenum serves as a stimulus for the secretion of bile. In a process called **emulsification,** bile salt micelles are secreted

into the duodenum and act as detergents to break up the fat droplets into tiny *emulsification droplets* of triglycerides. Note that emulsification is not chemical digestion—the bonds joining glycerol and fatty acids are not hydrolyzed by this process.

Case Investigation CLUES

Alan had fatty stools and a prolonged blood clotting time.

- Given what you know of Alan's condition, what could have caused his fatty stools?
- How might this relate to his prolonged clotting time? (*Hint:* vitamin K, needed for the formation of some clotting factors, is a fat-soluble vitamin.)

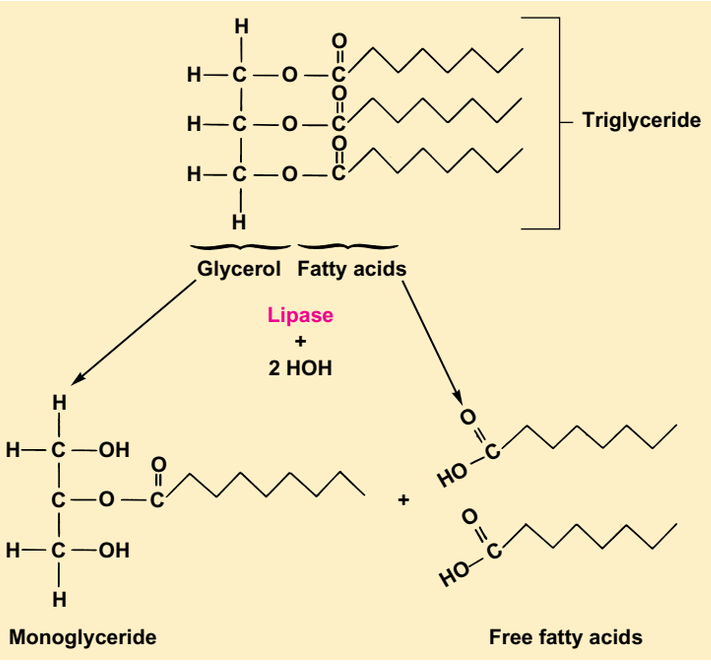


Figure 18.34 **The digestion of triglycerides.** Pancreatic lipase digests fat (triglycerides) by cleaving off the first and third fatty acids. This produces free fatty acids and monoglycerides. Sawtooth lines indicate hydrocarbon chains in the fatty acids.

Digestion of Lipids

The emulsification of fat aids digestion because the smaller and more numerous emulsification droplets present a greater surface area than the unemulsified fat droplets that originally entered the duodenum. Fat digestion occurs at the surface of the droplets through the enzymatic action of **pancreatic lipase,** which is aided in its action by a protein called *colipase* (also secreted by the pancreas) that coats the emulsification droplets and "anchors" the lipase enzyme to them. Through hydrolysis, lipase removes two of the three fatty acids from each triglyceride molecule and thus liberates *free fatty acids* and *monoglycerides* (fig. 18.34). **Phospholipase A** likewise digests phospholipids such as lecithin into fatty acids and *lysolecithin* (the remainder of the lecithin molecule after the removal of two fatty acids).

The free fatty acids, monoglycerides, and lysolecithin derived from the digested lipids are more polar than the undigested lipids. They quickly enter the micelles of bile salts, lecithin, and cholesterol from the bile to form *mixed micelles* in the duodenum (fig. 18.35). The mixed micelles then move to the brush border of the intestinal epithelium where absorption occurs.

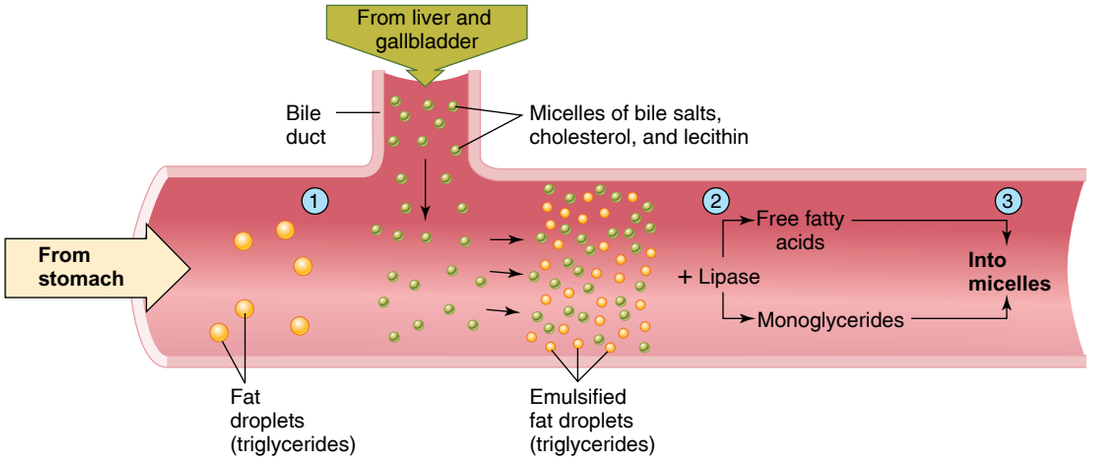
Absorption of Lipids

Free fatty acids, monoglycerides, and lysolecithin can leave the micelles and pass through the membrane of the microvilli to enter the intestinal epithelial cells. These products are then used to *resynthesize* triglycerides and phospholipids within the epithelial cells. This process is different from the absorption of amino acids and monosaccharides, which pass through the epithelial cells without being altered.

Triglycerides, phospholipids, and cholesterol are then combined with protein inside the epithelial cells to form small particles called **chylomicrons.** These tiny lipid and protein combinations are secreted into the central lacteals (lymphatic capillaries) of the intestinal villi (fig. 18.36). Absorbed lipids thus pass through the lymphatic system, eventually entering the venous blood by way of the thoracic duct (chapter 13, section 13.8). By contrast, amino acids and monosaccharides enter the hepatic portal vein.

Transport of Lipids in the Blood

Once the chylomicrons have entered the blood, they acquire a protein constituent, or *apolipoprotein,* called *ApoE.* (The structure of a lipoprotein particle is illustrated in chapter 13, fig. 13.32.) This allows the chylomicrons to bind to receptor proteins for ApoE located on the plasma membrane of capillary endothelial cells in the muscles and adipose tissue. The triglyceride content of the chylomicrons can then be digested by the enzyme *lipoprotein lipase,* which is also bound to the endothelial cell plasma membrane. The hydrolysis of triglyceride releases free fatty acids that can be used by skeletal muscles for energy and by adipose tissue for the synthesis of stored fat. After the triglyceride content of the chylomicrons has been removed, the remaining *remnant particle* containing cholesterol is released and travels in the circulation until it is taken up by the liver.



Step 1: Emulsification of fat droplets by bile salts

Step 2: Hydrolysis of triglycerides in emulsified fat droplets into fatty acid and monoglycerides

Step 3: Dissolving of fatty acids and monoglycerides into micelles to produce "mixed micelles"

Figure 18.35 **Fat digestion and emulsification.** The three steps indicate the fate of fat in the small intestine. The digestion of fat (triglycerides) releases fatty acids and monoglycerides, which become associated with micelles of bile salts secreted by the liver.

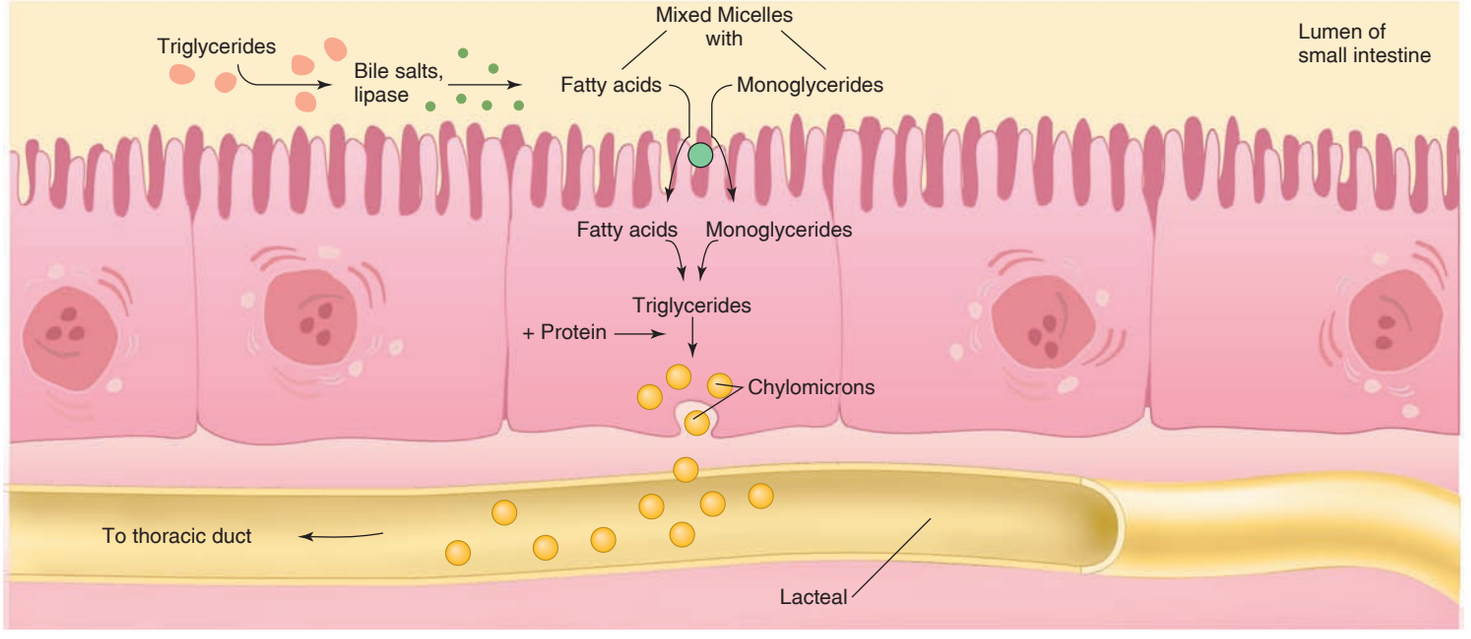


Figure 18.36 **The absorption of fat.** Fatty acids and monoglycerides from the micelles within the small intestine are absorbed by epithelial cells and converted intracellularly into triglycerides. These are then combined with protein to form chylomicrons, which enter the lymphatic vessels (lacteals) of the villi. These lymphatic vessels transport the chylomicrons to the thoracic duct, which empties them into the venous blood (of the left subclavian vein).

Table 18.8 | Characteristics of the Lipid Carrier Proteins (Lipoproteins) Found in Plasma

Lipoprotein Class	Origin	Destination	Major Lipids	Functions
Chylomicrons	Intestine	Many organs	Triglycerides, other lipids	Deliver lipids of dietary origin to body cells
Very-low-density lipoproteins (VLDLs)	Liver	Many organs	Triglycerides, cholesterol	Deliver endogenously produced triglycerides to body cells
Low-density lipoproteins (LDLs)	Intravascular removal of triglycerides from VLDLs	Blood vessels, liver	Cholesterol	Deliver endogenously produced cholesterol to various organs
High-density lipoproteins (HDLs)	Liver and intestine	Liver and steroid-hormone-producing glands	Cholesterol	Remove and degrade cholesterol

Cholesterol and triglycerides produced by the liver are combined with other apolipoproteins and secreted into the blood as **very-low-density lipoproteins (VLDLs),** which deliver triglycerides to different organs. Once the triglycerides are removed, the VLDL particles are converted to **low-density lipoproteins (LDLs),** which transport cholesterol to various organs, including blood vessels. This can contribute to the development of atherosclerosis (chapter 13, section 13.7). Excess cholesterol is returned from these organs to the liver attached to **high-density lipoproteins (HDLs).**

The HDL particles bind to receptors in the blood vessel wall and take up phospholipids and free cholesterol. An enzyme bonds the free cholesterol to the phospholipids, producing cholesterol esters. Because the cholesterol esters are very hydrophobic they move to the center of the HDL particle, enabling the particle to continue taking up free cholesterol from the cells of the blood vessel. After the HDL particle is fully loaded with cholesterol, it detaches from the vessel wall and travels to the liver to unload its cargo of cholesterol. As a result of this activity, a high ratio of HDL cholesterol to total cholesterol affords protection against atherosclerosis. The characteristics of the different lipoproteins are summarized in table 18.8.

CHECKPOINT

25. List the enzymes involved in carbohydrate digestion, indicating their origins, sites of action, substrates, and products.

26. List each enzyme involved in protein digestion, indicating its origin and site of action. Also, indicate whether the enzyme is an endopeptidase or exopeptidase.

27. Describe how bile aids both the digestion and absorption of fats. Explain how the absorption of fat differs from the absorption of amino acids and monosaccharides.

28. Trace the pathway and fate of a molecule of triglyceride and a molecule of cholesterol in a chylomicron within an intestinal epithelial cell.

29. Cholesterol in the blood may be attached to any of four possible lipoproteins. Distinguish among these proteins in terms of the origin and destination of the cholesterol they carry.