Digestive Enzymes

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METABOLISM

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Chapter 20
DIGESTIVE ENZYMES

p0140 Most dietary nutrients come in the form of large polymers that cannot be absorbed in the intact state. They have to be hydrolyzed by enzymes in the gastrointestinal (GI) tract, and the breakdown products, including monosaccharides, amino acids, and fatty acids, are absorbed. *The whole process of digestion consists of hydrolytic cleavage reactions.*

p0145 Approximately 30 g of digestive enzymes is secreted per day. Because each enzyme has a fairly narrow substrate specificity and hydrolyzes only certain bonds, several enzymes have to cooperate in the digestion of complex nutrients (***Table 20.1***).

s0010 SALIVA CONTAINS α-AMYLASE AND LYSOZYME

p0150 The main function of saliva is not the digestion of nutrients, but the conversion of food into a homogeneous mass during mastication. The only noteworthy enzymes in saliva are **α-amylase** and **lysozyme.** Both are classified as **endoglycosidases** because they cleave internal glycosidic bonds in a polysaccharide substrate. **Exoglycosidases,** in contrast, cleave glycosidic bonds at the ends.

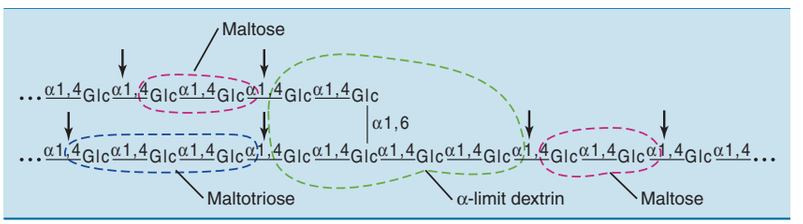
p0155 *α-Amylase cleaves α-1,4-glycosidic bonds in starch.* Starch occurs in two forms. **Amylose** is a linear polymer of several thousand glucose residues, linked by α(1→4) glycosidic bonds. **Amylopectin,** which usually forms the larger part of the starch in plants, is a branched molecule with α(1→6) glycosidic bonds at the branch points. **Glycogen,** the storage polysaccharide of animals, is similar to amylopectin but is even more branched.

p0160 α-Amylase does not cleave disaccharides and trisaccharides, and it is specific for α(1→4) bonds. Therefore it turns starch into **maltose, maltotriose,** and **α-limit dextrins** rather than free glucose (***Fig. 20.1***). Maltose is a disaccharide, and maltotriose is a trisaccharide of glucose residues in α(1→4) glycosidic linkage. α-Limit dextrins are oligosaccharides containing an α(1→6) glycosidic bond.

t0010 ***Table 20.1*** Dietary Nutrients and Their Fates in the Gastrointestinal Tract

Nutrient	Products Generated	Enzymes	Sites of Digestion
Starch, glycogen	Glucose	α-Amylase, disaccharidases, oligosaccharidases	Saliva, intestinal lumen, brush border
Maltose	Glucose	Glucoamylase, sucrase	Brush border
Sucrose	Glucose + fructose	Sucrase	
Lactose	Glucose + galactose	Lactase	
Proteins	Amino acids, dipeptides, tripeptides	Pepsin, pancreatic enzymes, brush border enzymes	Stomach, intestinal lumen, brush border
Triglycerides	Fatty acids, 2-monoacylglycerol	Pancreatic lipase	Intestinal lumen
Nucleic acids	Nucleosides, bases	DNAses, RNAses	Intestinal lumen
"Fiber": cellulose, lignin, hemicelluloses	Acetate, propionate, lactate, H_2, CH_4, CO_2		Only very limited fermentation by colon bacteria

DNAse, Deoxyribonuclease; *RNAse,* ribonuclease.



f0010 ***Fig. 20.1*** Pattern of starch digestion by α-amylase. This enzyme acts strictly as an endoglycosidase. It is unable to cleave the bonds in maltose, maltotriose, and the α-limit dextrins. *Arrows* indicate cleavage sites.

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p0165 The salivary α-amylase has its pH optimum at the normal salivary pH of 6.5 to 7.0. It can remain active in the stomach initially, but gets denatured when the food bolus is penetrated by gastric acid. Under most conditions, less than one-third of dietary starch is digested by salivary α-amylase. Its main function is to keep the teeth clean by dissolving starchy bits of food that remain lodged between the teeth after a meal. This is one reason why cancer patients whose salivary glands have been destroyed by radiation therapy develop rapid tooth decay.

p0170 The other salivary endoglycosidase, **lysozyme,** hydrolyzes β(1→4) glycosidic bonds in the bacterial cell wall polysaccharide **peptidoglycan** (***Fig. 20.2***). *Lysozyme kills some types of bacteria.* However, other bacteria are resistant because their peptidoglycan is protected from the enzyme by other cell wall components or, in the case of gram-negative bacteria, by an overlying outer membrane. The members of the normal bacterial flora in the mouth (including those that cause bad breath) are resistant to lysozyme. However, many bacteria from other ecosystems are killed by lysozyme. Animals make use of this effect by licking their wounds. They use their saliva as an antiseptic.

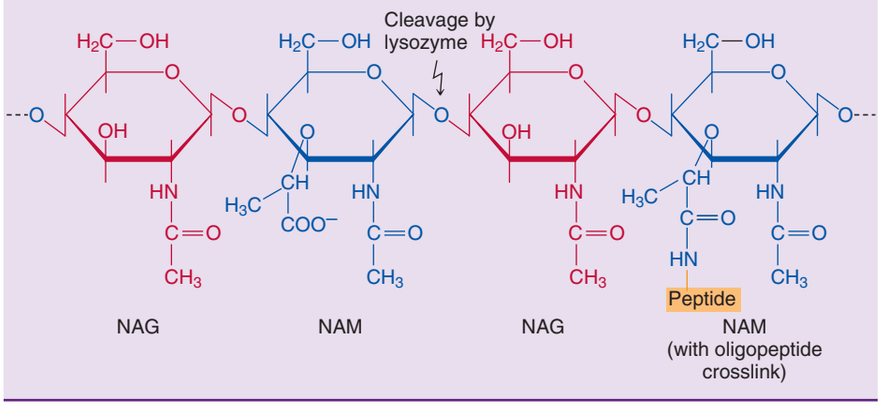
s0015

PROTEIN AND FAT DIGESTION START IN THE STOMACH

p0175 With a pH close to 2.0, the stomach is a forbidding place. The proton gradient between gastric juice and the blood—an almost million-fold concentration difference—is the steepest ion gradient anywhere in the body. The gastric acid has three major functions:

1. *It kills most microorganisms.* Because solid foods remain in the stomach far longer than do fluids, pathogens are more likely to establish an intestinal infection when they are ingested in water or other fluids than in solid food. People with achlorhydria (lack of gastric acid) and those who have had a gastrectomy (surgical removal of the stomach) have an increased risk of intestinal infections. o0010
2. *It denatures dietary proteins.* This helps with protein digestion because it makes the peptide bonds more accessible for proteases. o0015
3. *It is required for the action of* ***pepsin.*** Pepsin is a protease with an unusually low optimum pH of 2.0. It is considered an **endopeptidase,** although it also cleaves peptide bonds at the ends of the polypeptide. Pepsin cleaves only some peptide bonds, with a preference for bonds formed by the amino groups of large hydrophobic amino acids. Therefore it produces a mix of oligopeptides with some free amino acids. This mix is known as **peptone.** Protein digestion has to be completed by other enzymes in the small intestine (***Table 20.2***). o0020

p0195 In addition to protein, 10% to 20% of dietary fat is digested by an acid-tolerant gastric lipase that is secreted by the chief cells of the stomach. Neither gastric acid nor the gastric enzymes are essential for life. Patients can live reasonably normal lives after total gastrectomy, provided they receive supplements of vitamin B_{12}, whose absorption is greatly impaired in the absence of the gastric glycoprotein intrinsic factor (see Chapter 31).



f0015 ***Fig. 20.2*** Structure of peptidoglycan, the substrate of lysozyme. NAG, *N*-acetylglucosamine; NAM, *N*-acetylmuramic acid.

t0015 ***Table 20.2*** Enzymes of Protein Digestion

Enzyme	Source	Type	Catalytic Mechanism	Cleavage Specificity
Pepsin	Stomach	Endopeptidase	Carboxyl protease	NH side of hydrophobic amino acids
Trypsin	Pancreas	Endopeptidase	Serine protease	CO side of basic amino acids
Chymotrypsin	Pancreas	Endopeptidase	Serine protease	CO side of hydrophobic amino acids
Elastase	Pancreas	Endopeptidase	Serine protease	CO side of small amino acids
Carboxypeptidase A	Pancreas	Carboxypeptidase	Metalloprotease (Zn^{2+})	Hydrophobic amino acids at C-terminus
Carboxypeptidase B	Pancreas	Carboxypeptidase	Metalloprotease (Zn^{2+})	Basic amino acids at C-terminus

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s0020

THE PANCREAS IS A FACTORY FOR DIGESTIVE ENZYMES

p0200 When gastric contents enter the duodenum, the amino acids and fatty acids produced in the stomach become powerful stimuli for endocrine cells in the duodenum. These cells release the hormone **cholecystokinin** (CCK), also called **pancreozymin** because it stimulates both gallbladder contraction and pancreatic enzyme secretion. It induces its actions through the IP_3-calcium system. The acidity of the gastric contents entering the duodenum stimulates the release of **secretin.** Acting through the G_s protein and cyclic AMP, this hormone stimulates the secretion of water and bicarbonate from the pancreas.

p0205 Pancreatic juice supplies a cocktail of enzymes for the digestion of nearly all major nutrients. **α-Amylase** is secreted in large amounts. This enzyme is different from the salivary α-amylase, which has a slightly different structure (94% amino acid identity) and is encoded by a different gene. Closely related enzymes that catalyze the same reaction but differ in molecular structure, physical properties, and reaction kinetics are called **isoenzymes.**

p0210 For protein digestion, the pancreas supplies the endopeptidases (and exopeptidases) **trypsin, chymotrypsin,** and **elastase.** All three are serine proteases (see Chapter 4), but with different cleavage specificities. Their action is complemented by exopeptidases (see *Table 20.2*). Other pancreatic enzymes include **pancreatic lipase,** various **phospholipases,** and **nucleases.**

b0010

CLINICAL EXAMPLE 20.1: Orlistat

p0215 Excess fat in modern diets has been blamed for many adverse health outcomes, most obviously obesity. One strategy for reducing the impact of dietary fat is the prevention of fat digestion. One drug that is based on this principle is tetrahydrolipstatin, better known as Orlistat, which is synthesized from a bacterial metabolite. It inhibits gastric and pancreatic lipases by covalent binding to a serine residue in the active site of the enzyme, similar to the mechanism by which organophosphates inhibit acetylcholinesterase (see ***Clinical Example 4.2*** in Chapter 4). It does lead to weight reduction in some patients, and it may reduce the level of LDL cholesterol slightly by reducing the intestinal absorption of cholesterol and bile acids. However, it also causes the undesirable effects of fat malabsorption, including intestinal discomfort and mild diarrhea. The drug should be given with supplements of fat-soluble vitamins, whose absorption is reduced in the presence of undigested fat.

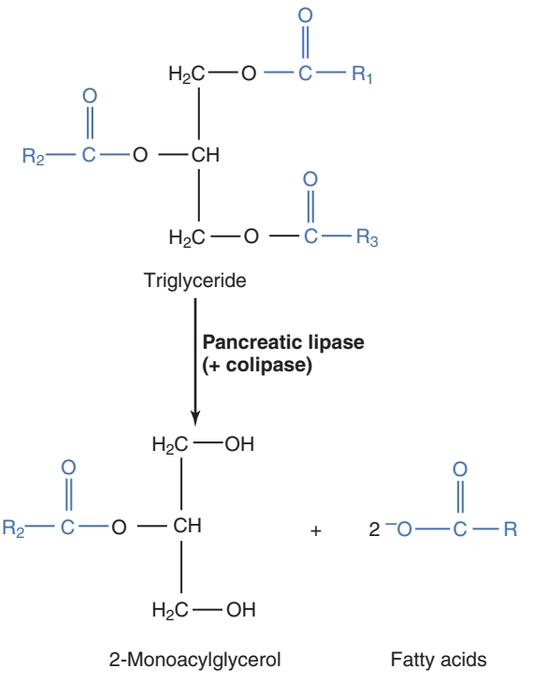
s0025

FAT DIGESTION REQUIRES BILE SALTS

p0220 Triglycerides do not dissolve in water. They form large fat droplets that provide only a small surface area for enzymatic attack, and the first task in fat digestion is to disperse the fat into smaller particles with a larger surface/volume ratio.

p0225 During mastication, fat is emulsified with the help of dietary phospholipids and proteins. In the stomach, this process continues with the help of fatty acids, monoglycerides, and diglycerides formed by the gastric lipase.

p0230 In the small intestine, **pancreatic lipase** and **colipase** bind to the surface of the emulsion droplets. The colipase maintains the activity of the lipase in the presence of bile salts, which would otherwise inhibit its activity. Pancreatic lipase hydrolyzes dietary triglycerides to free fatty acids and 2-monoacylglycerol (2-monoglyceride):



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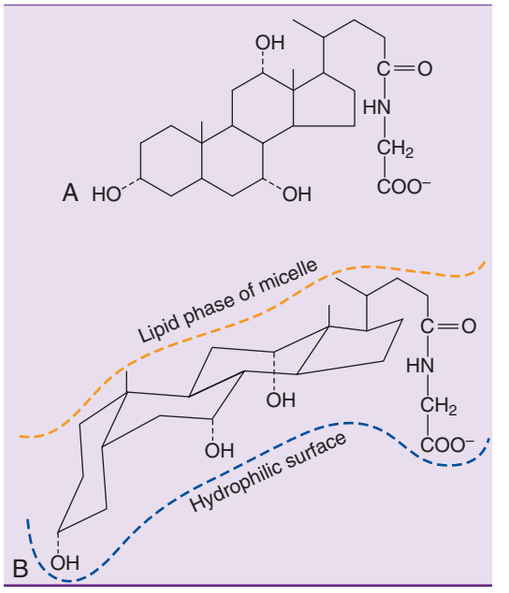


Fig. 20.3 Structure of glycocholate, the most abundant bile salt in humans. The protonated forms of the bile salts are called "bile acids." **A,** Structure. **B,** Stereochemistry. Note that the molecule has a hydrophilic surface and a hydrophobic surface.

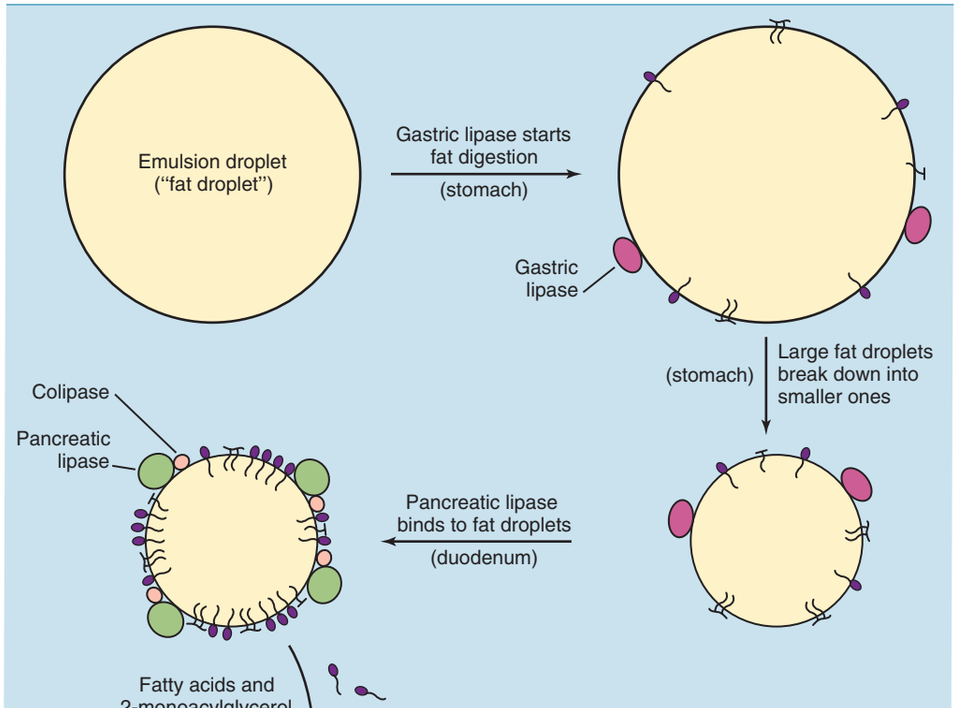
f0020

p0235 Unlike the triglycerides, *the products of fat digestion are slightly soluble in water.* They can diffuse to the intestinal brush border for absorption, but only to a very limited extent. Their efficient absorption requires **bile salts** (deprotonated bile acids), which are released into the intestine from the gallbladder after meals (***Fig. 20.3***). Between 20 and 50 g of bile salts reaches the intestine every day.

p0240 Bile salts are needed to form **mixed micelles,** which look like little shreds of lipid bilayer. The products of fat digestion form the two layers of the bilayer, and the bile salt covers the hydrophobic edges. *Mixed micelles ferry the lipids through the unstirred layer overlying the intestinal mucosa.* From the micelles, fatty acids and 2-monoglyceride diffuse to the microvilli for uptake into the mucosal cells (***Fig. 20.4***). Fatty acids with 18 and more carbons require bile salts for efficient absorption, but medium-chain fatty acids (C-8 to C-14) are absorbed quite well in their absence.

p0245 Bile salts are also needed for the absorption of other dietary lipids, including cholesterol and fat-soluble vitamins. In general, *lipids with the lowest water solubility are most dependent on bile salts for their absorption.*

p0250 **Fat malabsorption** can result from pancreatic failure, lack of bile salts due to biliary obstruction, or extensive intestinal diseases. Pancreatic failure leads to bulky, fatty, floating stools that contain undigested triglycerides.



f0025 ***Fig. 20.4*** Sequence of events in fat digestion. A small amount of fat is hydrolyzed by gastric lipase in the stomach, but pancreatic lipase is the major enzyme of fat digestion. Bile salts containing micelles are required for efficient absorption of fatty acids, monoglycerides, and other dietary lipids.

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This condition is called **steatorrhea,** defined by the presence of more than 7 to 15 g of fat in the stools per day. Fat-soluble vitamins can become deficient because they are excreted in the stools along with the fat, instead of being absorbed. A lack of bile salts has similar consequences, but in this case most of the "fat" in the stools consists of unabsorbed fatty acids, monoglycerides, and diglycerides.

b0015 **CLINICAL EXAMPLE 20.2: Pancreatic Enzyme Replacement Therapy**

p0255 Although the exocrine pancreas is involved in the digestion of all major nutrients, it is most important for fat digestion. In addition to diabetes mellitus, surgical removal of the pancreas causes serious fat malabsorption with steatorrhea and milder impairments in the digestion and absorption of other nutrients. The most common causes of exocrine pancreatic insufficiency are cystic fibrosis in children and chronic pancreatitis in adults. Standard treatment is enzyme replacement therapy. It consists of mixtures of enzymes obtained from swine or ox pancreas that are enteric-coated in small tablets or in microspheres of 1 to 2 mm diameter. The coating is stable under acidic conditions but dissolves at the duodenal pH of 5 to 6. Without enteric coating, the pancreatic lipase and other enzymes in these preparations would be destroyed by acid and pepsin in the stomach.

s0030 ## SOME DIGESTIVE ENZYMES ARE ANCHORED TO THE SURFACE OF THE MICROVILLI

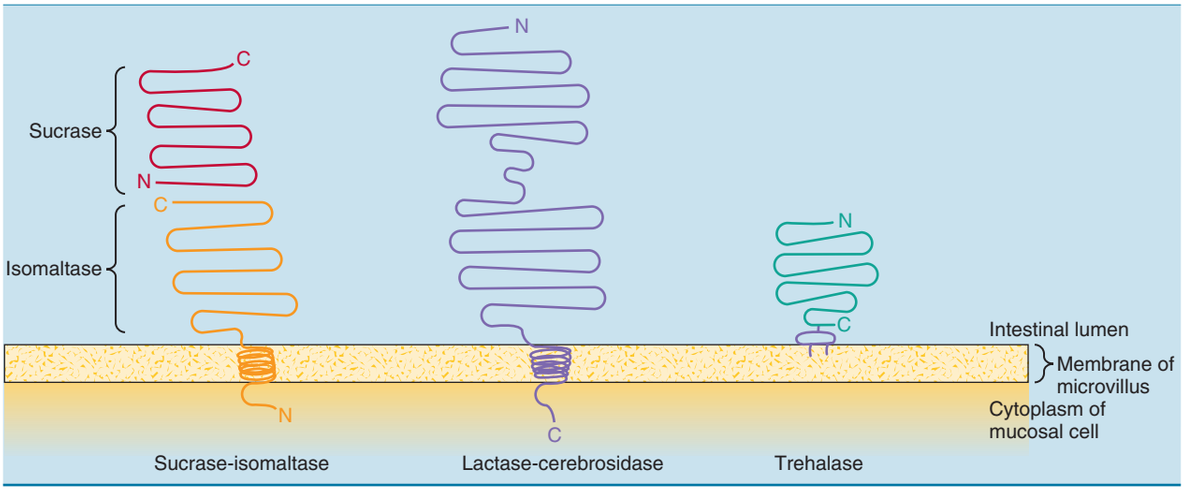
p0260 The crypts of Lieberkühn in the small intestine secrete between 1 and 2 L of a watery fluid every day, but this secretion is almost devoid of digestive enzymes. However, there are enzymes attached to the lumenal surface of the mucosal cells. This surface, known as the intestinal **brush border,** measures more than 200 m^2 because of the extensive folding of the villi and the innumerable microvilli. The brush border enzymes are firmly anchored to the surface of the microvilli, with their catalytic domains protruding into the intestinal lumen (***Fig. 20.5***).

p0265 **Disaccharidases** and **oligosaccharidases** (***Table 20.3***) hydrolyze sucrose and lactose, as well as the maltose, maltotriose, and α-limit dextrins that are formed by the action of α-amylase on starch.

p0270 The absorption of the monosaccharides requires specialized transporters in the apical (lumen-facing) and basolateral (blood-facing) membranes of the enterocytes. ***Fig. 20.6*** summarizes the absorption of the monosaccharides. Glucose and galactose are absorbed into the enterocyte by **SGLT1 (sodium-glucose transporter 1),** a high-affinity carrier that mediates the coupled transport of two sodium ions into the cell together with the sugar. Cotransport of sodium down its electrochemical gradient ensures complete absorption of the sugar from the intestinal lumen, but it requires ATP consumption by the sodium-potassium ATPase to restore the sodium gradient across the plasma membrane.

p0275 Transport of the monosaccharides across the basolateral membrane is by facilitated diffusion using **GLUT2 (glucose transporter 2).** When intestinal glucose concentration is high after a carbohydrate-rich meal, GLUT2 also becomes deposited in the apical membrane. Fructose is absorbed mainly by facilitated diffusion, using the bidirectional carrier **GLUT5** in the apical membrane and primarily GLUT2 in the basolateral membrane.

p0280 Why does glucose absorption require secondary active transport while fructose absorption is cost-free using only facilitated diffusion? The reason is that the glucose concentration in the blood is high at all times,



f0030 ***Fig. 20.5*** Anchoring of disaccharidases to the surface of the microvilli in the intestinal brush border. The sucrase-isomaltase complex is biosynthetically derived from a single polypeptide that is cleaved by pancreatic proteases. Isomaltase and lactase/cerebrosidase have transmembrane α-helices. Trehalase is anchored by glycosyl phosphatidylinositol (see ***Fig. 12.11***). All of these enzymes are glycoproteins.

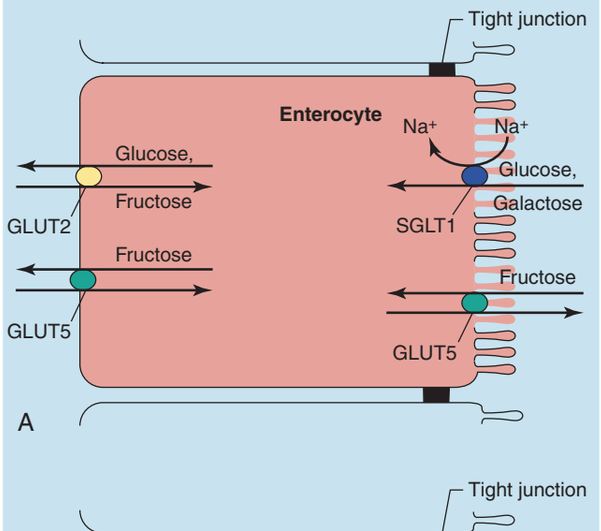
t0020 ***Table 20.3*** Disaccharidases and Oligosaccharidases of the Intestinal Brush Border

Enzyme	Cleavage Specificity
Glucoamylase	Maltose, maltotriose; acts as exoglycosidase on α-1,4 bonds at the nonreducing end of starch and starch-derived oligosaccharides
Sucrase	Sucrose, maltose, maltotriose
Isomaltase	α-1,6 Bonds in isomaltose and α-limit dextrins
Lactase*	Lactose; also cellobiose†
Cerebrosidase*	Glucocerebroside, galactocerebroside
Trehalase	Trehalose‡

*The lactase and cerebrosidase activities reside in two different globular domains of the same polypeptide (see ***Fig. 19.5***).

†Cellobiose is a disaccharide of two glucose residues in β-1,4-glycosidic linkage.

‡Trehalose is a disaccharide of two glucose residues in α,α′-1,1-glycosidic linkage; it is common only in mushrooms and insects.



f0035 ***Fig. 20.6*** Absorption of monosaccharides in the small intestine.

approximately 5 mmol/L (90 mg/dL). Therefore a passive transport system would not be able to bring the glucose concentration in the intestinal lumen below 90 mg/dL. Fructose, however, is metabolized so fast by the liver that the fructose level in the blood remains very low, even after a fructose-rich meal. Therefore ATP-dependent absorption against a concentration gradient is not required.

p0285 In addition to the glycosidases, the intestinal brush border contains several **peptidases** (proteases). Most of them are aminopeptidases that complete protein digestion by releasing free amino acids. The amino acids are absorbed into the enterocytes by sodium cotransporters and cross the basolateral membrane by facilitated diffusion.

p0290 A sizable portion of the dietary protein is absorbed not in the form of free amino acids, but as dipeptides and tripeptides. This requires the **PEPT1** (**peptide transporter 1**) carrier, which transports most di- and tripeptides into the cell together with a proton. This type of cotransport favors absorption over secretion because the pH of the intestinal contents is about 6 while the cytoplasmic pH in the enterocytes is about 7. Once in the cell, the di- and tripeptides are hydrolyzed to free amino acids by cytoplasmic enzymes.

POORLY DIGESTIBLE NUTRIENTS CAUSE FLATULENCE

s0035

p0295 In comparison with other animals, humans have a substandard digestive system. Although 95% of dietary fat and variable proportions of other dietary lipids are utilized, the efficiency of starch digestion is only 70% to 90% depending on the dietary source. Protein digestion is variable. Keratins and some plant proteins are incompletely digested, and between 5 to 20 g of protein is excreted in the stools every day. This includes undigested dietary protein and protein from digestive enzymes and desquamated mucosal cells.

p0300 Many plant polymers, including cellulose, hemicelluloses, inulin, pectin, lignin and suberin, are resistant to human digestive enzymes. A small percentage of this undigestible "dietary fiber" is hydrolyzed and fermented by the lush bacterial flora of the colon.

p0305 Under the strictly anaerobic conditions prevailing in the colon, bacterial fermentation produces **propionic acid** and **butyric acid** as the major end products. Most of this is absorbed and makes a modest contribution to our nutrition. The bacteria also produce a flammable gas consisting of **hydrogen, methane,** and **carbon dioxide,** which contributes to global warming because of its methane content.

p0310 Most troublesome are food components that are resistant to human digestive enzymes but are fermented rapidly by intestinal bacteria. Some vegetables contain oligosaccharides in which C-1 of galactose forms an α-1,6-glycosidic bond. These α-galactosides are resistant to digestive enzymes but are hydrolyzed rapidly by intestinal bacteria. **Raffinose** and **stachyose** in beans and peas are the most notorious examples (***Fig. 20.7***). The

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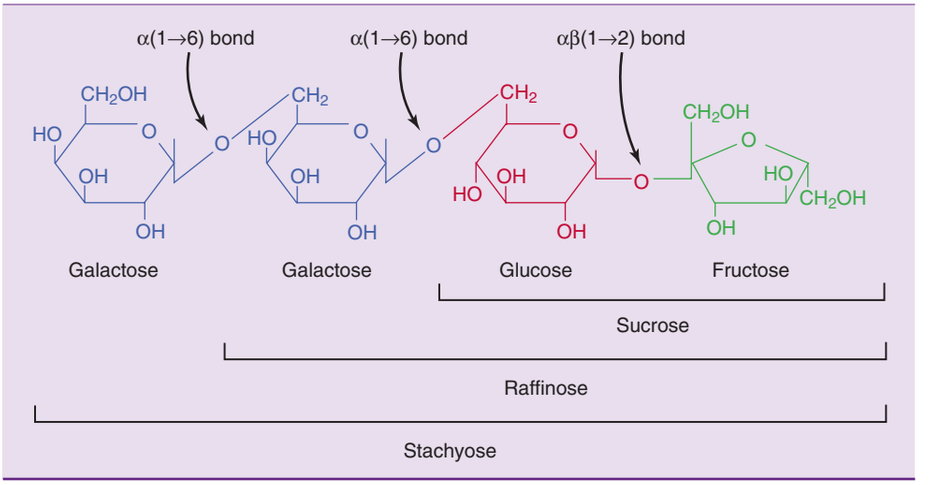


f0040 ***Fig. 20.7*** Structures of raffinose and stachyose. The α-1,6 bonds formed by galactose are undigestible but are hydrolyzed by bacterial α-galactosidases, leading to excessive bacterial growth and flatulence.

released monosaccharides are rapidly fermented to acids and gas in the colon. The acids can cause abdominal discomfort through their acidity and diarrhea through their osmotic activity; and the gas, though otherwise harmless, can be socially embarrassing.

s0040 ## MANY DIGESTIVE ENZYMES ARE RELEASED AS INACTIVE PRECURSORS

p0315 Among the digestive enzymes, *proteases and phospholipases are dangerous*. They must be kept chained and muzzled until they reach the lumen of the GI tract, lest they attack proteins and membrane lipids in the cells of their birth.

p0320 To prevent self-digestion, the dangerous enzymes (but not lipases and glycosidases) are synthesized and secreted as inactive precursors called **zymogens.** The zymogens are synthesized at the rough endoplasmic reticulum, stored in secretory vesicles, released by exocytosis, and activated by selective proteolytic cleavage in the lumen of the GI tract.

b0020 ## CLINICAL EXAMPLE 20.3: Lactose Intolerance

p0325 Lactose ("milk sugar") is abundant only in milk and milk products. Accordingly, the activity of intestinal lactase is maximal in infants. Some people maintain abundant lactase throughout life and can digest almost any amount of lactose. In other individuals, lactase declines to only 5% to 10% of the original level. The result is **lactose intolerance,** with flatulence and other intestinal symptoms after the consumption of more than 200 to 500 mL of milk. Avoiding excessive amounts of milk is the only "treatment" required. Also, lactose-free milk products and lactase in pill and capsule forms are commercially available. The latter products contain lactases of microbial origin.

p0330 In most parts of the world, a majority of the population is lactose intolerant. Persistent lactase prevails only in Europeans and in some desert nomads of Arabia and Africa (***Table 20.4***).

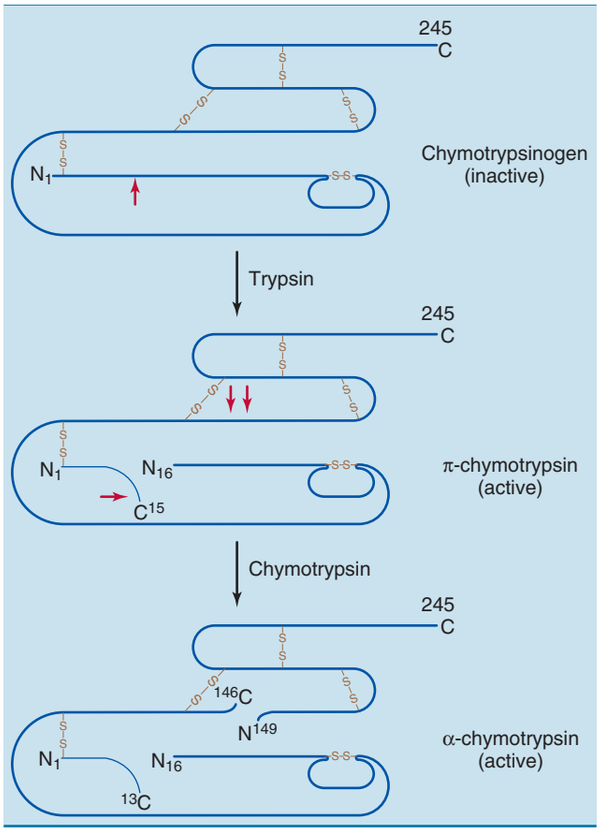
p0335 In Europe, lactase persistence is caused by a point mutation in an enhancer 13,910 base pairs upstream of the start of the lactase gene. This genetic variant became common only after the introduction of cattle raising and milking; it has not been found in fossil DNA from Europeans dated to between 5000 and 5800 years BC. It appears that lactase persistence was selected in Europe because those who could digest the milk of their animals were slightly more likely to survive and reproduce than were those who could not. Thus a Roman anthropologist reported about the Germans: "They do not eat much cereal food, but live chiefly on milk and meat…." (Caesar, *Gallic War*, 4.1).

t0025 ***Table 20.4*** Approximate Prevalence of Lactase Restriction (Nonpersistent Lactase) in Various Populations

Population/Country	Percent with Low Lactose-Digesting Capacity
Sweden	1
Britain	6
Germany	15
Greece	53
Morocco	78
Tuareg (Niger)	13
Fulani (Nigeria, Senegal)	0–22
Ibo, Yoruba (Nigeria)	89
Saudi Arabia: Bedouins	23
Saudi Arabia: Other Arabs	56
India (different areas)	27–67
Thailand	98
China	93–100
North American Indians	63–95

CLINICAL EXAMPLE 20.3: Lactose Intolerance—cont'd

p0345 Biochemically, lactose intolerance can be demonstrated in two ways. In the **lactose tolerance test,** the blood glucose level is determined before and after ingestion of 50 g of lactose. A rise in blood glucose of less than 20 mg/100 mL suggests lactose intolerance. Alternatively, the hydrogen content of breath can be determined before and after an oral lactose load. Increased hydrogen indicates fermentation of undigested lactose by colon bacteria.



f0045 ***Fig. 20.8*** Activation of chymotrypsinogen to chymotrypsin. These reactions take place in the duodenum. Although π-chymotrypsin is fully active, α-chymotrypsin is the predominant form in the small intestine.

p0350 **Pepsinogen** is secreted from the chief cells of the stomach. It is stable in the synthesizing cell, but the low pH in the gastric juice changes its conformation so that it cleaves itself to active pepsin. This reaction removes a 44–amino acid peptide from the amino terminus of pepsinogen. Even after this activating reaction, *pepsin is essentially inactive at pH values close to 7.0.*

p0355 The pancreatic zymogens include **trypsinogen, chymotrypsinogen** (***Fig. 20.8***), **proelastase, procarboxypeptidases,** and **prophospholipases.** *All of these zymogens are activated by trypsin in the intestinal lumen.* Trypsinogen itself is activated either by trypsin or by the duodenal brush border enzyme **enteropeptidase.**

p0360 The pancreas protects itself not only by synthesizing the dangerous enzymes as inactive zymogens but also by a **trypsin inhibitor,** a small (6-kD) polypeptide that binds very tightly (but noncovalently) to trypsin. It is present in the cytoplasm of the acinar cells and in the ductal system, where it inactivates any trypsin that is accidentally activated within the organ.

CLINICAL EXAMPLE 20.4: Acute Pancreatitis

b0025

p0365 The accidental activation of zymogens within the pancreatic duct system leads to **acute pancreatitis,** a life-threatening condition in which the pancreas digests itself. The enzymes even spill over into the abdominal cavity, where the pancreatic lipase finds ample substrate in the intraabdominal adipose tissue.

p0370 The cause of acute pancreatitis remains unknown in most cases. It is associated with alcoholism, and a gallstone blocking the ampulla of Vater can be demonstrated in some cases. Acute pancreatitis is diagnosed by determining the presence of lipase or amylase in the blood (see Chapter 17).

SUMMARY

s0045

p0375 Digestive enzymes are hydrolases that degrade macromolecular nutrients into their constituent monomers. Because the digestive enzymes have fairly narrow cleavage specificities, many enzymes have to cooperate for the complete digestion of nutrients.

p0380 Proteins are digested by pepsin in the stomach and by the pancreatic enzymes trypsin, chymotrypsin, elastase, carboxypeptidase A, and carboxypeptidase B in the lumen of the small intestine. Their digestion is completed by peptidases on the surface of the intestinal mucosal cells. Starch is digested to maltose, maltotriose, and α-limit dextrins by the pancreatic α-amylase. Together with sucrose and lactose, these products are hydrolyzed by brush border enzymes. Dietary triglycerides are digested to free fatty acids and 2-monoacylglycerol by pancreatic lipase, and these breakdown products are absorbed with the help of bile salts.

p0385 Digestive enzymes are products of the "secretory pathway." Proteases and phospholipases are synthesized as inactive zymogens, which are activated by partial proteolysis in the lumen of the GI tract.

Further Reading

fr0010

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eq0010 ## QUESTIONS

o0025 **1. A Chinese student at a U.S. medical school complains to the school physician that he suffers from bouts of flatulence and diarrhea shortly after each breakfast. His usual breakfast consists of two candy bars, a small bag of peanuts, and three glasses of fresh milk. He never had digestive problems in his home country, where his diet consisted only of vegetables, meat, and rice. He has most likely a low level of**

o0030 **A.** Pepsin
o0035 **B.** Pancreatic lipase
o0040 **C.** Lactase
o0045 **D.** Trypsin
o0050 **E.** α-Amylase

2. Patients who had a pancreatectomy (surgical removal of the pancreas) should take supplements of digestive enzymes with each meal. These enzyme supplements need not contain o0055

A. α-Amylase o0060
B. Proteases o0065
C. Lipase o0070
D. Disaccharidases o0075