Digestion, Absorption, and Transport of Carbohydrates

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Carbohydrates are the largest source of dietary calories for most of the world's population. The major carbohydrates in the US diet are starch, lactose, and sucrose. The **starches amylose** and **amylopectin** are polysaccharides composed of hundreds to millions of glucosyl units linked together through α-1,4- and α-1,6-glycosidic bonds (Fig. 21.1). **Lactose** is a disaccharide composed of glucose and galactose, linked together through a β-1,4-glycosidic bond. **Sucrose** is a disaccharide composed of glucose and fructose, linked through an α-1,2-glycosidic bond. The digestive processes convert all of these dietary carbohydrates to their constituent monosaccharides by **hydrolyzing glycosidic bonds** between the sugars.

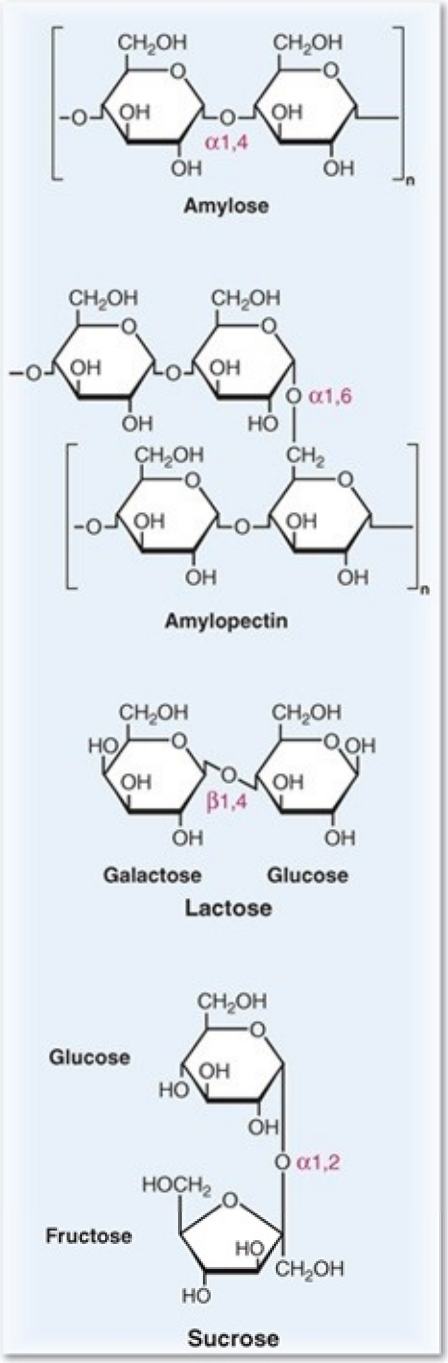


FIGURE 21.1 The structures of common dietary carbohydrates. For disaccharides and higher, the sugars are linked through glycosidic bonds between the anomeric carbon of one sugar and a hydroxyl group on another sugar. The glycosidic bond may be either α or β, depending on its position above or below the plane of the sugar containing the anomeric carbon. (See Chapter 5, Section II.A, to review terms used in the description of sugars.) The starch amylose is a polysaccharide of glucose residues linked with α-1,4-glycosidic bonds. Amylopectin is amylose with the addition of α-1,6-glycosidic branch points. Dietary sugars may be monosaccharides (single sugar residues), disaccharides (two sugar residues), oligosaccharides (several sugar residues), or polysaccharides (hundreds of sugar residues). For clarity, the hydrogen atoms are not shown in the figure.

The digestion of starch begins in the mouth (Fig. 21.2). The **salivary** gland

releases **α-amylase**, which converts starch to smaller polysaccharides called **α-dextrins**. Salivary α-amylase is inactivated by the acidity of the stomach (hydrochloric acid [HCl]). **Pancreatic α-amylase** and bicarbonate are secreted by the exocrine pancreas into the lumen of the small intestine, where bicarbonate neutralizes the gastric secretions. Pancreatic α-amylase continues the digestion of α-dextrins, converting them to disaccharides (**maltose**), trisaccharides (**maltotriose**), and oligosaccharides called **limit dextrins**. Limit dextrins usually contain four to nine glucosyl residues and an **isomaltose** branch (two glucosyl residues attached through an α-1,6-glycosidic bond).

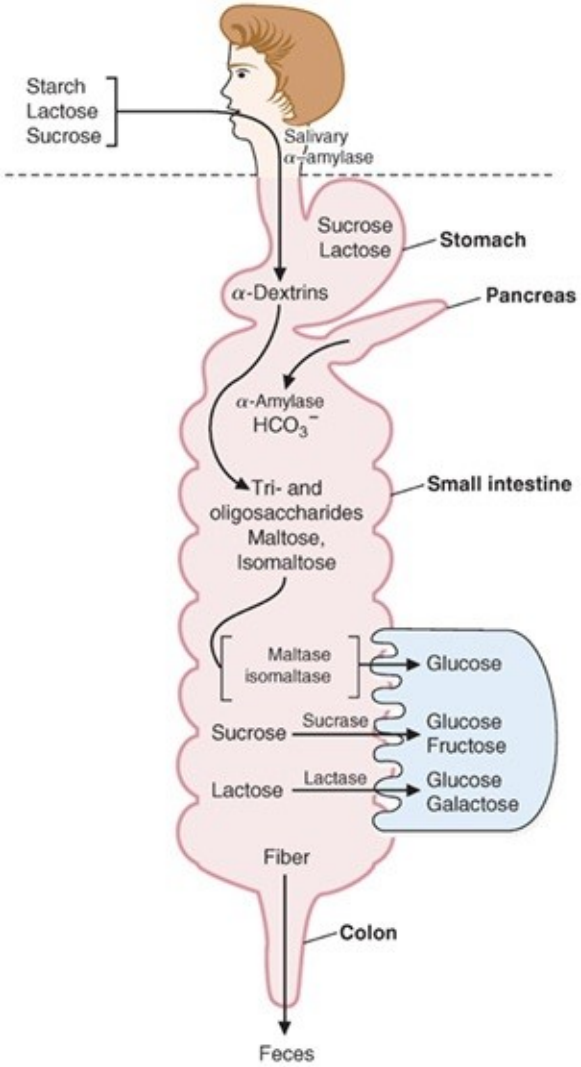


FIGURE 21.2 Overview of carbohydrate digestion. *Digestion* of the carbohydrates occurs first, followed by *absorption* of monosaccharides. Subsequent metabolic reactions occur after the sugars are absorbed.

The digestion of the disaccharides lactose and sucrose, as well as further

digestion of maltose, maltotriose, and limit dextrins, occurs through **disaccharidases** attached to the membrane surface of the **brush border** (**microvilli**) of intestinal epithelial cells. **Glucoamylase** hydrolyzes the α-1,4-bonds of dextrins. The **sucrase–isomaltase complex** hydrolyzes sucrose, most of maltose, and almost all of the isomaltose formed by glucoamylase from limit dextrins. **Lactase-glycosylceramidase** (β-glycosidase) hydrolyzes the β-glycosidic bonds in **lactose** and **glycolipids**. A fourth disaccharidase complex, **trehalase**, hydrolyzes the bond (an α-1,1-glycosidic bond) between two glucosyl units in the sugar trehalose. The monosaccharides produced by these hydrolases (glucose, fructose, and galactose) are then transported into the intestinal epithelial cells.

Dietary fiber, composed principally of polysaccharides, cannot be digested by enzymes in the human intestinal tract. In the colon, dietary fiber and other nondigested carbohydrates may be converted to gases (H_2, CO_2, and methane) and short-chain fatty acids (principally acetic acid, propionic acid, and butyric acid) by bacteria in the colon.

Glucose, **galactose**, and **fructose** formed by the digestive enzymes are transported into the absorptive epithelial cells of the small intestine by protein-mediated **Na^+-dependent active transport** and **facilitative diffusion**. Monosaccharides are transported from these cells into the blood and circulate to the liver and peripheral tissues, where they are taken up by facilitative transporters. Facilitative transport of glucose across epithelial cells and other cell membranes is mediated by a family of **tissue-specific glucose transport proteins** (**GLUT 1 to GLUT 5**). The type of transporter found in each cell reflects the role of glucose metabolism in that cell.

THE WAITING ROOM

Denise V. is a 20-year-old exchange student from Nigeria who has noted gastrointestinal bloating, abdominal cramps, and intermittent diarrhea ever since arriving in the United States 6 months ago. A careful history shows that these symptoms occur most commonly about 45 minutes to 1 hour after eating breakfast but may occur after other meals as well. Dairy products, which were

not a part of Denise's diet in Nigeria, were identified as the probable offending agent because her gastrointestinal symptoms disappeared when milk and milk products were eliminated from her diet.

Deborah S.'s fasting and postprandial blood glucose levels are frequently above the normal range in spite of good compliance with insulin therapy. Her physician has referred her to a dietician skilled in training diabetic patients in the successful application of an appropriate American Diabetes Association diet. As part of the program, Ms. S. is asked to incorporate foods containing fiber into her diet, such as whole grains (e.g., wheat, oats, corn), legumes (e.g., peas, beans, lentils), tubers (e.g., potatoes, peanuts), and fruits.

Nina M. is a 13-month-old baby girl, the second child born to unrelated parents. Her mother had a healthy, full-term pregnancy, and Nina's birth weight was normal. She did not respond well to breastfeeding and was changed entirely to a formula based on cows' milk at 6 weeks. Between 9 and 18 weeks of age, she was admitted to the hospital twice with a history of screaming after feeding but was discharged after observation without a specific diagnosis. Elimination of cows' milk from her diet did not relieve her symptoms; Nina's mother reported that when Nina turned 1 year old and she introduced some fruit juice into her diet, the screaming bouts were worse, particularly after drinking juice. She also noticed that Nina frequently had gas and a distended abdomen. She was still thriving (weight >97th percentile), with no abnormal findings on physical examination. A stool sample was taken.

The dietary sugar in fruit juice and other sweets is sucrose, a disaccharide composed of glucose and fructose joined through their anomeric carbons. **Nina M.'s** symptoms of pain and abdominal distension are caused by an inability to digest sucrose or absorb fructose, which are converted to gas by colonic bacteria. The possibility of carbohydrate malabsorption was considered, and a hydrogen breath test was recommended.

I. Dietary Carbohydrates

Carbohydrates are the largest source of calories in the average American diet and usually constitute 40% to 45% of our caloric intake. The plant starches *amylopectin* and *amylose*, which are present in grains, tubers, and vegetables, constitute approximately 50% to 60% of the carbohydrate calories consumed. These starches are polysaccharides, containing 10,000 to 1 million glucosyl units. In amylose, the glucosyl residues form a straight chain linked via α-1,4-glycosidic bonds; in amylopectin, the α-1,4-chains contain branches connected via α-1,6-glycosidic bonds (see Fig. 21.1). The other major sugar found in fruits and vegetables is *sucrose*, a disaccharide of glucose and fructose (see Fig. 21.1). Sucrose and small amounts of the monosaccharides *glucose* and *fructose* are the major natural sweeteners found in fruit, honey, and vegetables. *Dietary fiber*, the part of the diet that cannot be digested by human enzymes of the intestinal tract, is also composed principally of plant polysaccharides and a polymer called *lignin*.

Most foods derived from animals, such as meat or fish, contain very little carbohydrate except for small amounts of glycogen (which has a structure similar to amylopectin) and glycolipids. The major dietary carbohydrate of animal origin is lactose, a disaccharide composed of glucose and galactose that is found exclusively in milk and milk products (see Fig. 21.1). Sweeteners, in the form of sucrose and high-fructose corn syrup (starch, partially hydrolyzed and isomerized to fructose), also appear in the diet as additives to processed foods. On average, a person in the United States consumes 65 lb of added sucrose and 40 lb of high-fructose corn syrup solids per year.

Although all cells require glucose for metabolic functions, neither glucose nor other sugars are specifically required in the diet. Glucose can be synthesized from many amino acids found in dietary protein. Fructose, galactose, xylulose, and all the other sugars required for metabolic processes in the human can be synthesized from glucose.

Starch blockers were marketed many years ago as a means of losing weight without having to exercise or reduce your daily caloric intake. Starch blockers were based on a protein found in beans,

which blocked the action of amylase. Thus, as the advertisements proclaimed, one could eat a large amount of starch during a meal, and as long as you took the starch blocker, the starch would pass through the digestive tract without being metabolized. Unfortunately, this was too good to be true, and starch blockers were never shown to be effective in aiding weight loss. This was probably because of a combination of factors, such as inactivation of the inhibitor by the low pH in the stomach, and an excess of amylase activity as compared with the amount of starch blocker ingested. Recently, this issue has been revisited because a starch blocker from wheat has been developed that may work as advertised, although much more research is required to determine whether this amylase inhibitor will be safe and effective in humans. In addition, newer (and improved) preparations of the bean extract are also being readvertised.

II. Digestion of Dietary Carbohydrates

In the digestive tract, dietary polysaccharides and disaccharides are converted to monosaccharides by *glycosidases*, enzymes that hydrolyze the glycosidic bonds between the sugars. All of these enzymes exhibit some specificity for the sugar, the glycosidic bond (α or β), and the number of saccharide units in the chain. The monosaccharides formed by glycosidases are transported across the intestinal mucosal cells into the interstitial fluid and subsequently enter the bloodstream. Undigested carbohydrates enter the colon, where bacteria may ferment them.

A. Salivary and Pancreatic α-Amylase

The digestion of starch (amylopectin and amylose) begins in the mouth, where chewing mixes the food with saliva. The salivary glands secrete approximately 1 L of liquid per day into the mouth, containing *salivary α-amylase* and other components. α-Amylase is an *endoglycosidase*, which means that it hydrolyzes internal α-1,4-bonds between glucosyl residues at random intervals in the polysaccharide chains (Fig. 21.3). The shortened polysaccharide chains that are formed are called *α-dextrins*. Salivary α-amylase is largely inactivated by the

acidity of the stomach contents, which contain HCl secreted by the parietal cells.

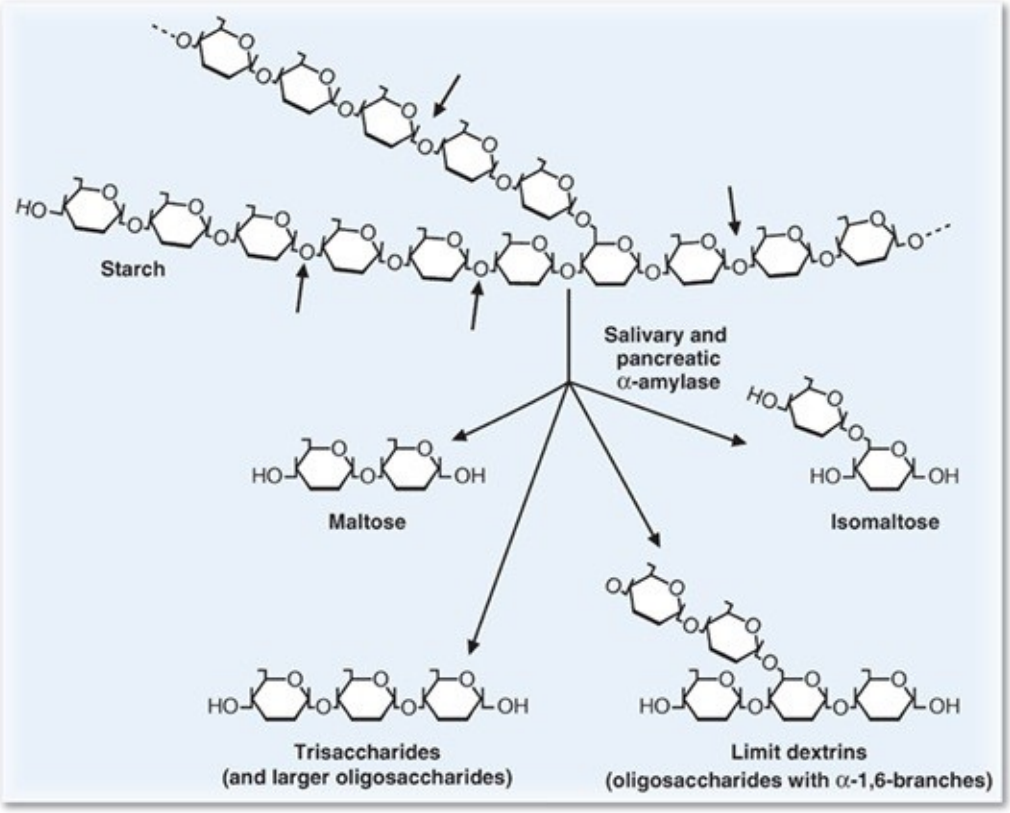


FIGURE 21.3 Action of salivary and pancreatic α-amylases.

The acidic gastric juice enters the duodenum, the upper part of the small intestine, where digestion continues. Secretions from the exocrine pancreas (~1.5 L/day) flow down the pancreatic duct and also enter the duodenum. These secretions contain bicarbonate (HCO_3^-), which neutralizes the acidic pH of stomach contents, and digestive enzymes, including pancreatic α-amylase.

Pancreatic α-amylase continues to hydrolyze the starches and glycogen, forming the disaccharide maltose, the trisaccharide maltotriose, and oligosaccharides. These oligosaccharides, called *limit dextrins*, are usually four to nine glucosyl units long and contain one or more α-1,6-branches. The two glucosyl residues that contain the α-1,6-glycosidic bond eventually become the disaccharide isomaltose.

Amylase activity in the gut is abundant and is not normally rate-limiting for the process of digestion. Alcohol-induced pancreatitis

or surgical removal of part of the pancreas can decrease pancreatic secretion. Pancreatic exocrine secretion into the intestine also can be decreased because of cystic fibrosis (as in **Susan F.**; see Chapter 17), in which mucus blocks the pancreatic duct, which eventually degenerates. However, pancreatic exocrine secretion can be decreased to 10% of normal and still not affect the rate of starch digestion because amylases are secreted in the saliva and pancreatic fluid in excessive amounts. In contrast, protein and fat digestion are more strongly affected in cystic fibrosis.

α-Amylase has no activity toward sugar-containing polymers other than glucose linked by α-1,4-bonds. α-Amylase displays no activity toward the α-1,6-bond at branch points and has little activity for the α-1,4-bond at the nonreducing end of a chain.

Acarbose is a U.S. Food and Drug Administration–approved drug that blocks the activities of pancreatic α-amylase and brush-border α-glucosidases (with a specificity for glucose). The drug is produced from a microorganism and is a unique tetrasaccharide. Acarbose can be used in patients with type 2 diabetes. It reduces the rate at which ingested carbohydrate reaches the bloodstream after a meal, but flatulence and diarrhea (caused by colonic bacterial metabolism of the nondigested sugars) are side effects of taking this drug, and thus, it is not used very often.

B. Disaccharidases of the Intestinal Brush-Border Membrane

The dietary disaccharides lactose and sucrose, as well as the products of starch digestion, are converted to monosaccharides by glycosidases attached to the membrane in the brush border of absorptive cells. The different glycosidase activities are found in four glycoproteins: glucoamylase, the sucrase–isomaltase complex, the smaller glycoprotein trehalase, and lactase-glucosylceramidase (Table 21.1). These glycosidases are collectively called the *small intestinal*

disaccharidases, although glucoamylase is really an oligosaccharidase.

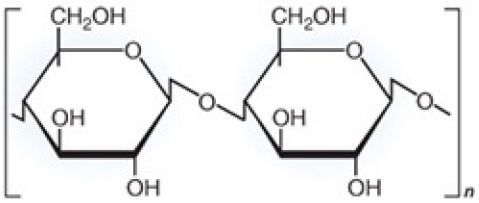
TABLE 21.1 The Different Forms of the Brush-Border Glycosidases

COMPLEX	CATALYTIC SITES	PRINCIPAL ACTIVITIES
β-Glucoamylase	α-Glucosidase	Split α-1,4-glycosidic bonds between glucosyl units, beginning sequentially with the residue at the tail end (nonreducing end) of the chain. This is an exoglycosidase. Substrates include amylose, amylopectin, glycogen, and maltose.
	β-Glucosidase	Same as above but with slightly different specificities and affinities for the substrates
Sucrase	Sucrase–maltase	Splits sucrose, maltose, and maltotriose
Isomaltase	Isomaltase–maltase	Splits α-1,-6-bonds in several limit dextrins as well as the α-1,4-bonds in maltose and maltotriose
β-Glycosidase	Glucosyl–ceramidase	Splits β-glycosidic bonds between glucose or galactose and hydrophobic residues, such as the glycolipids glucosylceramide and galactosylceramide; also known as *phlorizin hydrolase* for its activity on an artificial substrate
	Lactase	Splits the β-1,4-bond between glucose and galactose; to a lesser extent also splits the β-1,4-bond between some cellulose disaccharides
Trehalase	Trehalase	Splits bond in trehalose, which is two glucosyl units linked α-1,1 through their anomeric carbons

1. Glucoamylase

Glucoamylase and the sucrase–isomaltase complex have similar structures and exhibit a great deal of sequence homogeneity. A membrane-spanning domain near the *N* terminus attaches the protein to the luminal membrane. The long polypeptide chain forms two globular domains, each with a catalytic site. In glucoamylase, the two catalytic sites have similar activities, with only small differences in substrate specificity. The protein is heavily glycosylated, with oligosaccharides that protect it from digestive proteases.

Can the glycosidic bonds of the structure shown here be hydrolyzed by α-amylose?



A No. This polysaccharide is cellulose, which contains β-1,4-glycosidic bonds. Pancreatic and salivary α-amylase cleave only α-1,4-bonds between glucosyl units.

Glucoamylase is an *exoglycosidase* that is specific for the α-1,4-bonds between glucosyl residues (Fig. 21.4A). It begins at the nonreducing end of a polysaccharide or limit dextrin, and it sequentially hydrolyzes the bonds to release glucose monosaccharides. It will digest a limit dextrin down to isomaltose, the glucosyl disaccharide with an α-1,6-branch, that is subsequently hydrolyzed principally by the isomaltase activity in the sucrase–isomaltase complex.

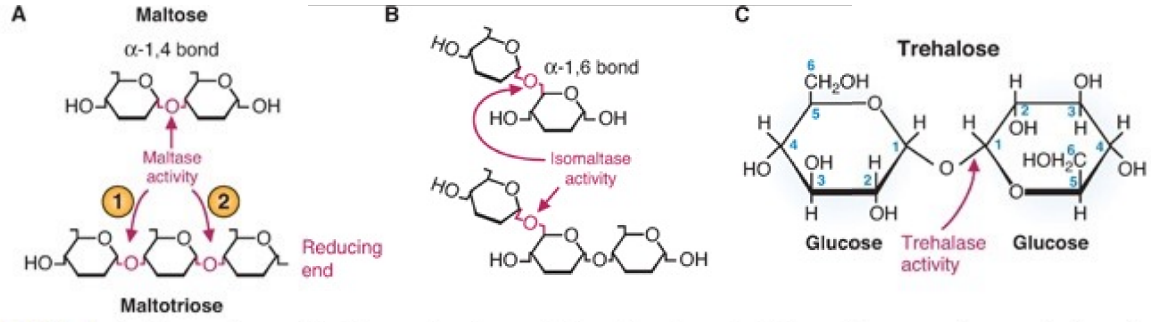


FIGURE 21.4 **A.** Glucoamylase activity. Glucoamylase is an α-1,4-exoglycosidase that initiates cleavage at the nonreducing end of the sugar. Thus, for maltotriose, the bond labeled *1* is hydrolyzed first, which then allows the bond at position *2* to be the next one hydrolyzed. **B.** Isomaltase activity. *Arrows* indicate the α-1,6-bonds that are cleaved. **C.** Trehalose. This disaccharide contains two glucose moieties linked by an unusual bond that joins their anomeric carbons. It is cleaved by trehalase.

2. Sucrase–Isomaltase Complex

The structure of the sucrase–isomaltase complex is similar to that of glucoamylase, and these two proteins have a high degree of sequence homology. However, after the single polypeptide chain of sucrase–isomaltase is inserted through the membrane and the protein protrudes into the intestinal lumen, an intestinal protease clips it into two separate subunits that remain attached to each other through noncovalent interactions. Each subunit has a catalytic site that

differs in substrate specificity from the other through noncovalent interactions. The sucrase–maltase site accounts for approximately 100% of the intestine's ability to hydrolyze sucrose in addition to maltase activity; the isomaltase–maltase site accounts for almost all of the intestine's ability to hydrolyze α-1,6-bonds (see Fig. 21.4B), in addition to maltase activity. Together, these sites account for approximately 80% of the maltase activity of the small intestine. The remainder of the maltase activity is found in the glucoamylase complex.

Individuals with genetic deficiencies of the sucrase–isomaltase complex show symptoms of sucrose intolerance but are able to digest normal amounts of starch in a meal without problems. The maltase activity in the glucoamylase complex, and residual activity in the sucrase–isomaltase complex (which is normally present in excess of need), is apparently sufficient to digest normal amounts of dietary starch.

3. Trehalase

Trehalase is only half as long as the other disaccharidases and has only one catalytic site. It hydrolyzes the glycosidic bond in trehalose, a disaccharide composed of two glucosyl units linked by an α-bond between their anomeric carbons (see Fig. 21.4C). Trehalose, which is found in insects, algae, mushrooms, and other fungi, is not currently a major dietary component in the United States. However, unwitting consumption of trehalose can cause nausea, vomiting, and other symptoms of severe gastrointestinal distress if consumed by an individual deficient in the enzyme. Trehalase deficiency was discovered when a woman became very sick after eating mushrooms and was initially thought to have α-amanitin poisoning.

4. β-Glycosidase Complex (Lactase-Glucosylceramidase)

The β-glycosidase complex is another large glycoprotein found in the brush border that has two catalytic sites extending in the lumen of the intestine. However, its primary structure is very different from that of the other enzymes, and it is attached to the membrane through its carboxyl end by a phosphatidylglycan anchor (see Fig. 10.6). The lactase catalytic site hydrolyzes

the β-bond connecting glucose and galactose in lactose (a β-galactosidase activity; Fig. 21.5). The major activity of the other catalytic site in humans is the β-bond between glucose or galactose and ceramide in glycolipids (this catalytic site is sometimes called *phlorizin hydrolase*, named for its ability to hydrolyze an artificial substrate).

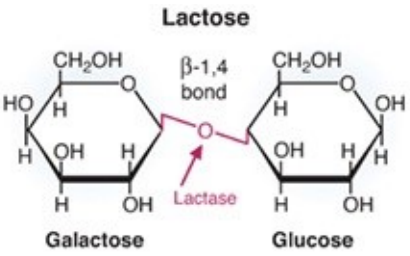
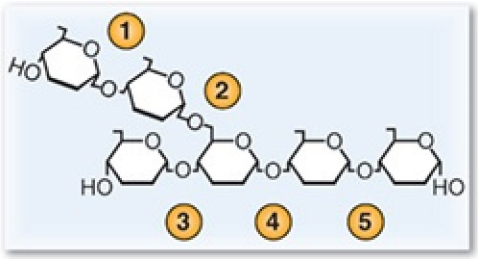


FIGURE 21.5 Lactase activity. Lactase is a β-galactosidase. It cleaves the β-galactoside lactose, the major sugar in milk, forming galactose and glucose.

Q Which of the bonds in the structure shown here are hydrolyzed by the sucrase–isomaltase complex? Which by glucoamylase?



A Bonds (*1*) and (*3*) would first be hydrolyzed by glucoamylase. Bond (*2*) requires isomaltase. Bonds (*4*) and (*5*) can then be hydrolyzed by the sucrase–isomaltase complex or by the glucoamylase complex, all of which can convert maltotriose and maltose to glucose.

5. Location Within the Intestine

The production of maltose, maltotriose, and limit dextrins by pancreatic α-amylase occurs in the duodenum, the most proximal portion of the small intestine. Sucrase–isomaltase activity is highest in the jejunum, where the

enzymes can hydrolyze sucrose and the products of starch digestion. β-Glycosidase activity is also highest in the jejunum. Glucoamylase activity increases progressively along the length of the small intestine, and its activity is highest in the ileum. Thus, it presents a final opportunity for digestion of starch oligomers that have escaped amylase and disaccharidase activities at the more proximal regions of the intestine.

C. Metabolism of Sugars by Colonic Bacteria

Not all of the starch ingested as part of foods is normally digested in the small intestine (Fig. 21.6). Starches that are high in amylose, or are less well-hydrated (e.g., starch in dried beans), are resistant to digestion and enter the colon. Dietary fiber and undigested sugars also enter the colon. Here, colonic bacteria rapidly metabolize the saccharides, forming gases, short-chain fatty acids, and lactate. The major short-chain fatty acids formed are acetic acid (two carbons), propionic acid (three carbons), and butyric acid (four carbons). The short-chain fatty acids are absorbed by the colonic mucosal cells and can provide a substantial source of energy for these cells. The major gases formed are hydrogen gas (H_2), carbon dioxide (CO_2), and methane (CH_4). These gases are released through the colon, resulting in flatulence, or through the breath. Incomplete products of digestion in the intestines increase the retention of water in the colon, resulting in diarrhea.

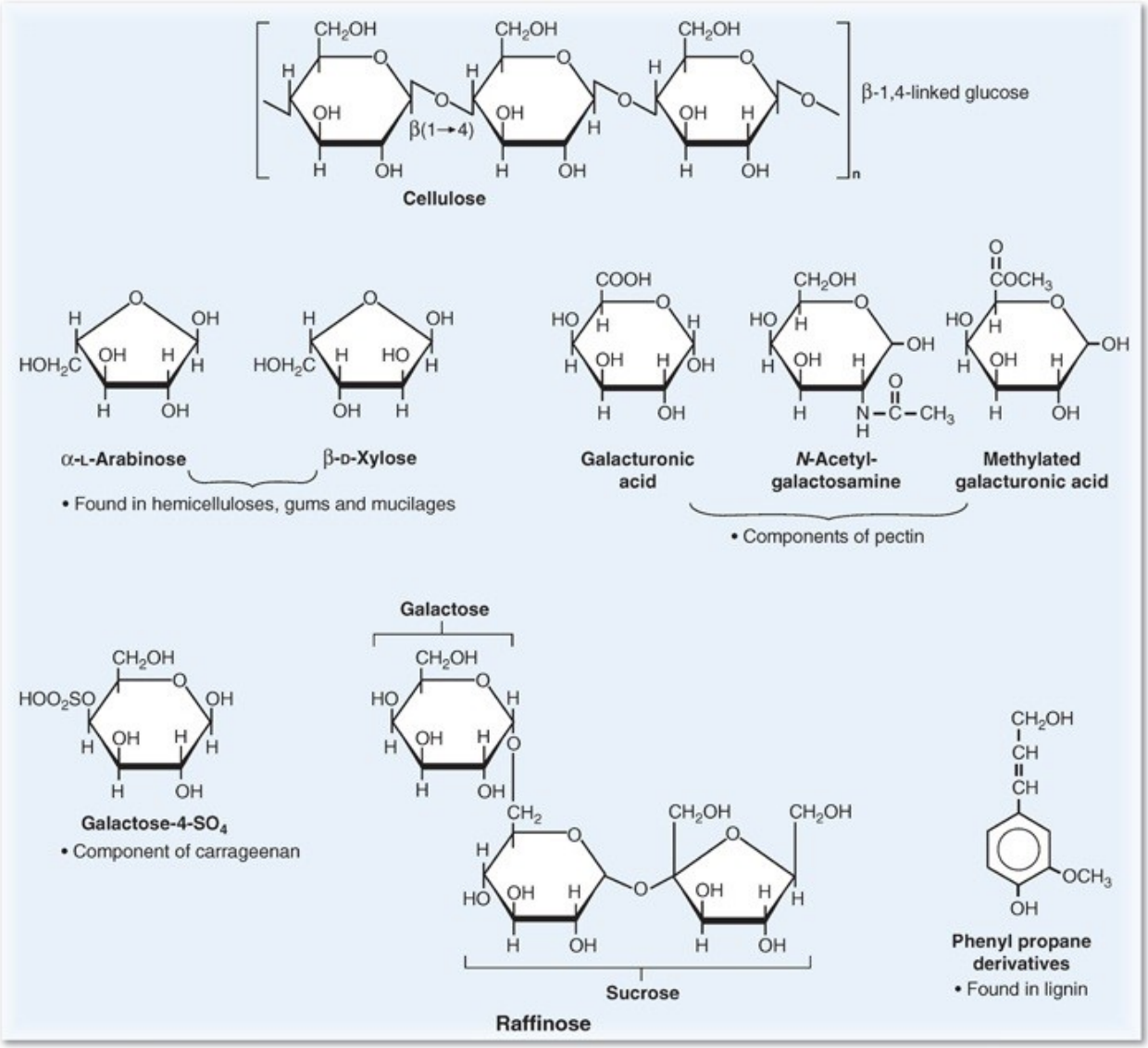


FIGURE 21.6 Some indigestible carbohydrates. These compounds are components of dietary fiber.

D. Lactose Intolerance

Lactose intolerance refers to a condition of pain, nausea, and flatulence after the ingestion of foods containing lactose, most notably dairy products. Although lactose intolerance is often caused by low levels of lactase, it also can be caused by intestinal injury (defined in the following text).

Nina M. was given a hydrogen breath test, a test measuring the amount of hydrogen gas released after consuming a test dose of

sugar. In this test, the patient breathes into a portable meter or a collecting bag attached to a nonportable device. The larger, nonportable devices measure the hydrogen in the breath via gas chromatography. The portable devices measure the hydrogen gas produced using hydrogen-specific electrodes and measuring a current that is created when hydrogen comes into contact with the electrode. The association of Nina's symptoms with her ingestion of fruit juices suggests that she might have a problem resulting from low sucrase activity or an inability to absorb fructose. Her ability to thrive and her adequate weight gain suggest that any deficiencies of the sucrase–isomaltase complex must be partial and do not result in a functionally important reduction in maltase activity (maltase activity is also present in the glucoamylase complex). Her urine tested negative for sugar, suggesting that the problem is in digestion or absorption because only sugars that are absorbed and enter the blood can be found in urine. The basis of the hydrogen breath test is that if a sugar is not absorbed, it is metabolized in the intestinal lumen by bacteria that produce various gases including hydrogen. The test can be accompanied by measurements of the amount of sugar that appear in the blood or feces, and acidity of the feces.

1. Nonpersistent and Persistent Lactase

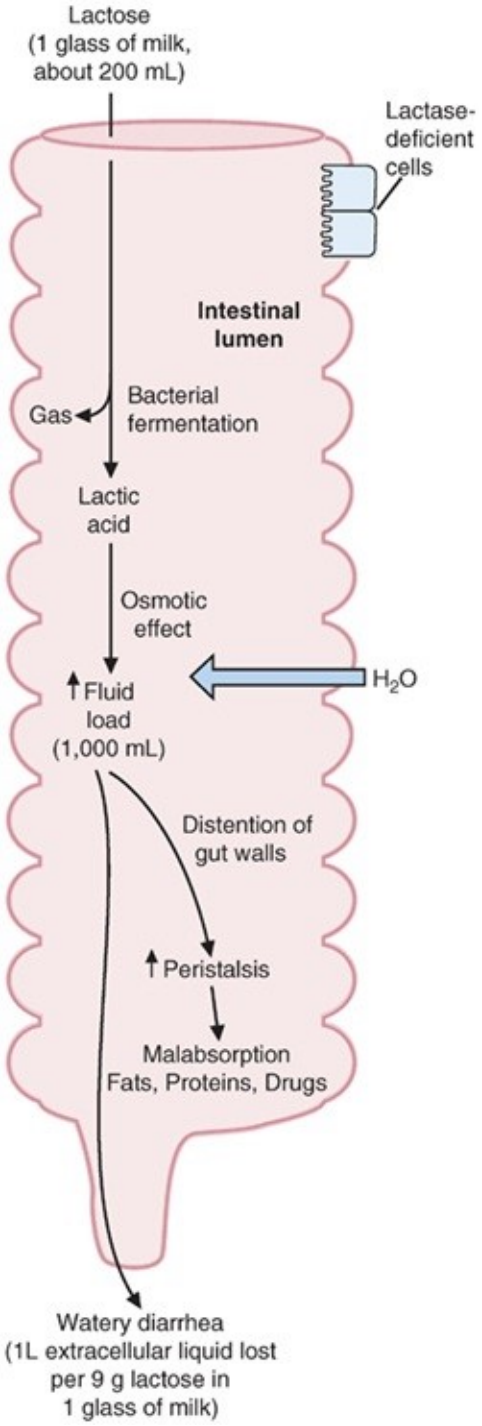
Lactase activity increases in the human from about 6 to 8 weeks of gestation, and it rises during the late gestational period (21 to 32 weeks) through full term. It remains high for about 1 month after birth and then begins to decline. For most of the world's population, lactase activity decreases to adult levels at approximately 5 to 7 years of age. Adult levels are <10% of those present in infants. These populations have *adult hypolactasia* (formerly called *adult lactase deficiency*) and exhibit the lactase nonpersistence phenotype. In people who are derived mainly from Western Northern Europeans, and milk-dependent Nomadic tribes of Saharan Africa, the levels of lactase remain at, or only slightly below, infant levels throughout adulthood (lactase persistence phenotype). Thus, adult hypolactasia is the normal condition for most of the world's population (Table 21.2).

TABLE 21.2 Prevalence of Late-Onset Lactase Deficiency	
GROUP	**PREVALENCE (%)**
US Population	
Asians	100
American Indians (Oklahoma)	95
Black Americans	81
Mexican Americans	56
White Americans	24
Other Populations	
Ibo, Yoruba (Nigeria)	89
Italians	71
Aborigines (Australia)	67
Greeks	53
Danes	3
Dutch	0

In contrast, *congenital lactase deficiency* is a severe autosomal-recessive inherited disease in which lactase activity is significantly reduced or totally absent. The disorder presents as soon as the newborn is fed breast milk or lactose-containing formula, resulting in watery diarrhea, weight loss, and dehydration. Treatment consists of removal of lactose from the diet, which allows for normal growth and development to occur.

2. Intestinal Injury

Intestinal diseases that injure the absorptive cells of the intestinal villi diminish lactase activity along the intestine, producing a condition known as *secondary lactase deficiency*. Kwashiorkor (protein malnutrition), colitis, gastroenteritis, tropical and nontropical sprue, and excessive alcohol consumption fall into this category. These diseases also affect other disaccharidases, but sucrase, maltase, isomaltase, and glucoamylase activities are usually present at such excessive levels that there are no pathologic effects. Lactase is usually the first activity lost and the last to recover.



Lactose intolerance can either be the result of a primary deficiency of lactase production in the small bowel (as is the case for **Denise V.**), or it can be secondary to an injury to the intestinal mucosa, where lactase is normally produced. The lactose that is not absorbed is

converted by colonic bacteria to lactic acid, methane gas (CH_4), and H_2 gas (see the following figure). The osmotic effect of the lactose and lactic acid in the bowel lumen is responsible for the diarrhea that is often seen as part of this syndrome. Similar symptoms can result from sensitivity to milk proteins (milk intolerance) or from the malabsorption of other dietary sugars.

In adults suspected of having a lactase deficiency, the diagnosis is usually made inferentially when avoidance of all dairy products results in relief of symptoms and a rechallenge with these foods reproduces the characteristic syndrome. If the results of these measures are equivocal, however, the malabsorption of lactose can be determined more specifically by measuring the H_2 content of the patient's breath after a test dose of lactose has been consumed.

Denise V.'s symptoms did not appear if she took available over-the-counter tablets containing lactase when she ate dairy products.

III. Dietary Fiber

Dietary fiber is the portion of the diet resistant to digestion by human digestive enzymes. It consists principally of plant materials that are polysaccharide derivatives and lignan (see Fig. 21.6). The components of fiber are often divided into the categories of soluble and insoluble fiber, according to their ability to dissolve in water. Insoluble fiber consists of three major categories: cellulose, hemicellulose, and lignins. Soluble fiber categories include pectins, mucilages, and gums (Table 21.3). Although human enzymes cannot digest fiber, the bacterial flora in the normal human gut may metabolize the more soluble dietary fibers to gases and short-chain fatty acids, much as they do undigested starch and sugars. Some of these fatty acids may be absorbed and used by the colonic epithelial cells of the gut, and some may travel to the liver through the hepatic portal vein. We may obtain as much as 10% of our total calories from compounds produced by bacterial digestion of substances in our digestive tract.

TABLE 21.3 **Types of Fiber in the Diet**

CLASSICAL NOMENCLATURE	CLASSES OF COMPOUNDS	DIETARY SOURCES
Insoluble Fiber		
Cellulose	Polysaccharide composed of glucosyl residues linked β-1,4	Whole-wheat flour, unprocessed bran, vegetables
Hemicelluloses	Polymers of arabinoxylans or galactomannans	Bran cereals, whole grains,
Lignin	Noncarbohydrate, polymeric derivatives of phenylpropane	Fruits and edible seeds, mature vegetables
Water-Soluble Fiber (or Dispersible)		
Pectic substances	Galacturonans, arabinogalactans, β-glucans, arabinoxylans	Apples, strawberries, carrots, citrus
Gums	Galactomannans, arabinogalactans	Oats, legumes, guar, barley
Mucilages	Wide range of branched and substituted galactans	Flax seed, psyllium, mustard seed

The 2015 Dietary Guideline Advisory Committee issued guidelines for fiber ingestion—anywhere from 22 to 34 g/day in adults, depending on the age and sex of the individual. No distinction was made between soluble and insoluble fibers. Adult males between the ages of 19 and 30 years require 34 g of fiber per day. Males between 31 and 50 years of age require 30.8 g of fiber per day. Males older than 51 years of age are recommended to consume 28 g of fiber per day. Adult women between 19 and 30 years of age require 28 g/day. Women between the ages of 31 and 50 years of age are recommended to consume 25.2 g of fiber per day. Women older than 51 years of age are recommended to consume 22 g of fiber per day. These numbers are increased during pregnancy and lactation. One beneficial effect of fiber is seen in diverticular disease in which sacs or pouches may develop in the colon because of a weakening of the muscle and submucosal structures. Fiber is thought to "soften" the stool, thereby reducing pressure on the colonic wall and enhancing expulsion of feces.

Certain types of soluble fiber have been associated with disease prevention. For example, pectins may lower blood cholesterol levels by binding bile acids. β-Glucan (obtained from oats) has also been shown, in some studies, to reduce cholesterol levels through a reduction in bile acid resorption in the intestine (see Chapter 32). Pectins also may have a beneficial effect in the diet of individuals with diabetes mellitus by slowing the rate of absorption of simple sugars and preventing high blood glucose levels after meals. However, each of the beneficial effects that have been related to "fiber" is relatively specific for the

type of fiber and the physical form of the food that contains the fiber. This factor, along with many others, has made it difficult to obtain conclusive results from studies of the effects of fiber on human health.

Beans, peas, soybeans, and other leguminous plants contain oligosaccharides with linked galactose residues that cannot be hydrolyzed for absorption, including sucrose with one, two, or three galactose residues attached (see Fig. 21.6). What is the fate of these polysaccharides in the intestine?

These sugars are not digested well by the human intestine but form good sources of energy for the bacteria of the gut. These bacteria convert the sugars to H_2, lactic acid, and short-chain fatty acids. The amount of gas released after a meal containing beans is especially notorious.

IV. Absorption of Sugars

Once the carbohydrates have been split into monosaccharides, the sugars are transported across the intestinal epithelial cells and into the blood for distribution to all tissues. Not all complex carbohydrates are digested at the same rate within the intestine, and some carbohydrate sources lead to a near-immediate rise in blood glucose levels after ingestion, whereas others slowly raise blood glucose levels over an extended period after ingestion. The *glycemic index* of a food is an indication of how rapidly blood glucose levels rise after consumption. Glucose and maltose have the highest glycemic indices (defined as 100). Table 21.4 indicates the glycemic index for a variety of food types. Although there is no need to memorize this table, note that cornflakes and potatoes have high glycemic indices, whereas yogurt and skim milk have particularly low glycemic indices.

TABLE 21.4 Glycemic Indices of Selected Foods, with Values Adjusted to Glucose of 100

Breads		**Legumes**	
Whole wheat	74	Soya beans	16
Specialty grain bread	53	Lentils	32
Pasta		Chick peas	28
Spaghetti, white, boiled	49	Kidney beans (dried)	24
Cereal Grains		Peanuts	15
Barley	28	**Fruit**	
White rice (boiled)	73	Banana	51
Brown rice (boiled)	68	Apple	36
Sweet corn	52	Apple juice	41
Breakfast Cereals		Orange	43
Wheat flake biscuits	69	Watermelon	76
Cornflakes	81	**Sugars**	
Muesli	57	Maltose	105
Snacks		Fructose	15
Popcorn	65	Glucose	100
Chocolate	40	Honey	61
Root Vegetables		Sucrose	65
Potatoes (instant, mash)	87	**Dairy Products**	
Potato (new, white, boiled)	78	Ice cream	51
Potato, French fries	63	Whole milk	39
Sweet potato, boiled	63	Skim milk	37
		Yogurt, fruit	41

Data from Atkinson FS, Foster-Powell K, Brand-Miller JC. International tables of glycemic index and glycemic load values. *Diabetes Care*. 2008;31(12):2281–2283.

The glycemic response to ingested foods depends not only on the glycemic index of the foods but also on the fiber and fat content of the food as well as its method of preparation. Highly glycemic carbohydrates can be consumed before and after exercise because their metabolism results in a rapid entry of glucose into the blood, where it is then immediately available for use by muscle cells. Low-glycemic carbohydrates enter the circulation slowly and can be used to best advantage if consumed before exercise, such that as exercise progresses, glucose is slowly being absorbed from the intestine into the circulation, where it can be used to maintain blood glucose levels during the exercise period.

The dietitian explained to **Deborah S.** the rationale for a person with diabetes to follow a carbohydrate-controlled diet using meal-planning tools such as carbohydrate counting (www.diabetes.org, click on *Food and Fitness*). It is important for Deborah to add a variety of fibers, particularly soluble fiber, to her diet. The gel-forming, water-retaining pectins and gums found in foods such as oatmeal, nuts, beans,

lentils, and apples delay gastric emptying and retard the rate of absorption of disaccharides and monosaccharides, thus reducing the rate at which blood glucose levels rise. Although research has shown that the total amount of carbohydrate is most influential on blood glucose levels, the quality of carbohydrate—the glycemic index of foods—may also need to be considered for optimal maintenance of blood glucose levels in people with diabetes. Consumption of a low-glycemic-index diet results in a lower rise in blood glucose levels after eating, which can be more easily controlled by exogenous insulin. For example, **Ms. S.** is advised to eat pasta and barley (glycemic indices of 49 and 28, respectively) instead of potatoes (glycemic index of 63 to 87, depending on the method of preparation) and to incorporate breakfast cereals composed of wheat bran, barley, and oats into her morning routine. Because the total amount and the type of carbohydrate influence blood glucose levels, Deborah is advised to consume lower glycemic index foods in appropriate portions.

A. Absorption by the Intestinal Epithelium

Glucose is transported through the absorptive cells of the intestine by facilitated diffusion and by Na^+-dependent facilitated transport. (See Chapter 10 for a description of transport mechanisms.) The glucose molecule is extremely polar and cannot diffuse through the hydrophobic phospholipid bilayer of the cell membrane. Each hydroxyl group of the glucose molecule forms at least two hydrogen bonds with water molecules, and random movement would require energy to dislodge the polar hydroxyl groups from their hydrogen bonds and to disrupt the van der Waals forces between the hydrocarbon tails of the fatty acids in the membrane phospholipid. Glucose, therefore, enters the absorptive cells by binding to transport proteins, membrane-spanning proteins that bind the glucose molecule on one side of the membrane and release it on the opposite side. Two types of glucose transport proteins are present in the intestinal absorptive cells: the Na^+-dependent glucose transporters and the facilitative glucose transporters (Fig. 21.7).

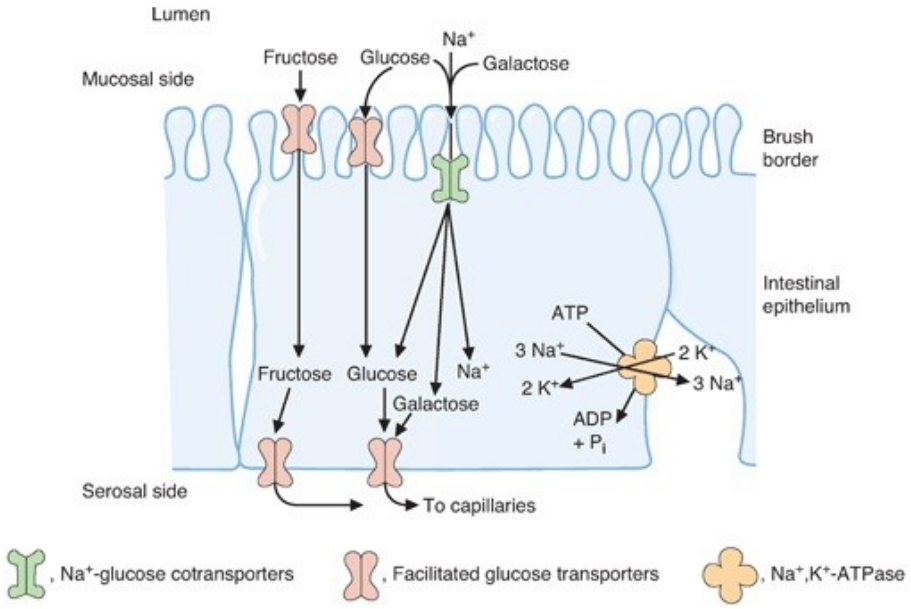


FIGURE 21.7 Na^+-dependent and facilitative transporters in the intestinal epithelial cells. Both glucose and fructose are transported by the facilitated glucose transporters on the luminal and serosal sides of the absorptive cells. Glucose and galactose are transported by the Na^+-glucose cotransporters on the luminal (mucosal) side of the absorptive cells. *ADP*, adenosine diphosphate; *ATP*, adenosine triphosphate; P_i, inorganic phosphate.

1. Na^+-Dependent Transporters

Na^+-dependent glucose transporters, which are located on the luminal side of the absorptive cells, enable these cells to concentrate glucose from the intestinal lumen. A low intracellular Na^+ concentration is maintained by a Na^+,K^+-ATPase on the serosal (blood) side of the cell that uses the energy from adenosine triphosphate (ATP) cleavage to pump Na^+ out of the cell into the blood. Thus, the transport of glucose from a low concentration in the lumen to a high concentration in the cell is promoted by the cotransport of Na^+ from a high concentration in the lumen to a low concentration in the cell (secondary active transport). Similar transporters are found in the epithelial cells of the kidney, which are thus able to transport glucose against its concentration gradient.

2. Facilitative Glucose Transporters

Facilitative glucose transporters, which do not bind Na^+, are located on the serosal side of the cells. Glucose moves via the facilitative transporters from the high concentration inside the cell to the lower concentration in the blood without the expenditure of energy. In addition to the Na^+-dependent glucose transporters, facilitative transporters for glucose also exist on the luminal side of the absorptive cells. The best characterized facilitative glucose transporters found in

the plasma membranes of cells (referred to as *GLUT 1* to *GLUT 5*) are described in Table 21.5. One common structural theme to these proteins is that they all contain 12 membrane-spanning domains. Note that the sodium-linked transporter on the luminal side of the intestinal epithelial cell is not a member of the GLUT family.

TABLE 21.5 Properties of the GLUT 1 to GLUT 5 Isoforms of the Glucose Transport Proteins

TRANSPORTER	TISSUE DISTRIBUTION	COMMENTS
GLUT 1	Human erythrocyte Blood–brain barrier Blood–retinal barrier Blood–placental barrier Blood–testis barrier	Expressed in cell types with barrier functions; a high-affinity glucose transport system
GLUT 2	Liver Kidney Pancreatic β-cell Serosal surface of intestinal mucosa cells	A high-capacity, low-affinity transporter May be used as the glucose sensor in the pancreas
GLUT 3	Brain (neurons)	Major transporter in the central nervous system; a high-affinity system
GLUT 4	Adipose tissue Skeletal muscle Heart muscle	Insulin-sensitive transporter; in the presence of insulin, the number of GLUT 4 transporters increases on the cell surface; a high-affinity system
GLUT 5	Intestinal epithelium Spermatozoa	This is actually a fructose transporter.

Genetic techniques have identified additional GLUT transporters (GLUT 6 to GLUT 12), but the roles of these transporters have not yet been fully described.

The epithelial cells of the kidney, which reabsorb glucose from the lumen of the renal tubule back into the blood, have Na^+-dependent glucose transporters similar to those of intestinal epithelial cells. They are thus also able to transport glucose against its concentration gradient. Other types of cells use mainly facilitative glucose transporters that carry glucose down its concentration gradient.

3. Galactose and Fructose Absorption through Glucose Transporters

Galactose is absorbed through the same mechanisms as glucose. It enters the absorptive cells on the luminal side via the Na^+-dependent glucose transporters and facilitative glucose transporters and is transported through the serosal side on the facilitative glucose transporters.

Fructose both enters and leaves absorptive epithelial cells by facilitated

diffusion, apparently via transport proteins that are part of the GLUT family. The transporter on the luminal side has been identified as GLUT 5. Although this transporter can transport glucose, it has a much higher activity with fructose (see Fig. 21.7). Other fructose transport proteins also may be present. For reasons as yet unknown, fructose is absorbed at a much more rapid rate when it is ingested as sucrose than when it is ingested as a monosaccharide.

B. Transport of Monosaccharides into Tissues

The properties of the GLUT transport proteins differ among tissues, reflecting the function of glucose metabolism in each tissue. In most cell types, the rate of glucose transport across the cell membrane is not rate-limiting for glucose metabolism. This is because the isoform of transporter present in these cell types has a relatively low K_m for glucose (i.e., a low concentration of glucose will result in half the maximal rate of glucose transport) or is present in relatively high concentration in the cell membrane so that the intracellular glucose concentration reflects that in the blood. Because the enzyme that initially metabolizes glucose in these (named *hexokinase*; see Chapter 22) cells has an even lower K_m for glucose (0.05 to 0.10 mM), variations in blood glucose levels do not affect the intracellular rate of glucose metabolism. However, in several tissues, the rate of transport becomes rate limiting when the serum level of glucose is low or when low levels of insulin signal the absence of dietary glucose.

The erythrocyte (red blood cell) is an example of a tissue in which glucose transport is not rate-limiting. Although the glucose transporter (GLUT 1) has a K_m of 1 to 7 mM, it is present in extremely high concentrations, constituting approximately 5% of all membrane proteins. Consequently, as the blood glucose levels fall from a postprandial level of 140 mg/dL (7.5 mM) to the normal fasting level of 80 mg/dL (4.5 mM), or even the hypoglycemic level of 40 mg/dL (2.2 mM), the supply of glucose is still adequate for the rates at which glucose-dependent metabolic pathways operate.

In the liver, the K_m for the glucose transporter (GLUT 2) is relatively high compared with that of other tissues, probably ≥15 mM. This is in keeping with the liver's role as the organ that maintains blood glucose levels. Thus, the liver

will convert glucose into other energy storage molecules only when blood glucose levels are high, such as the time immediately after ingesting a meal. In muscle and adipose tissue, the transport of glucose is greatly stimulated by insulin. The mechanism involves the recruitment of glucose transporters (specifically, GLUT 4) from intracellular vesicles into the plasma membrane (Fig. 21.8). In adipose tissue, the stimulation of glucose transport across the plasma membrane by insulin increases its availability for the synthesis of fatty acids and glycerol from the glycolytic pathway. In skeletal muscle, the stimulation of glucose transport by insulin increases its availability for energy generation (glycolysis) and glycogen synthesis.

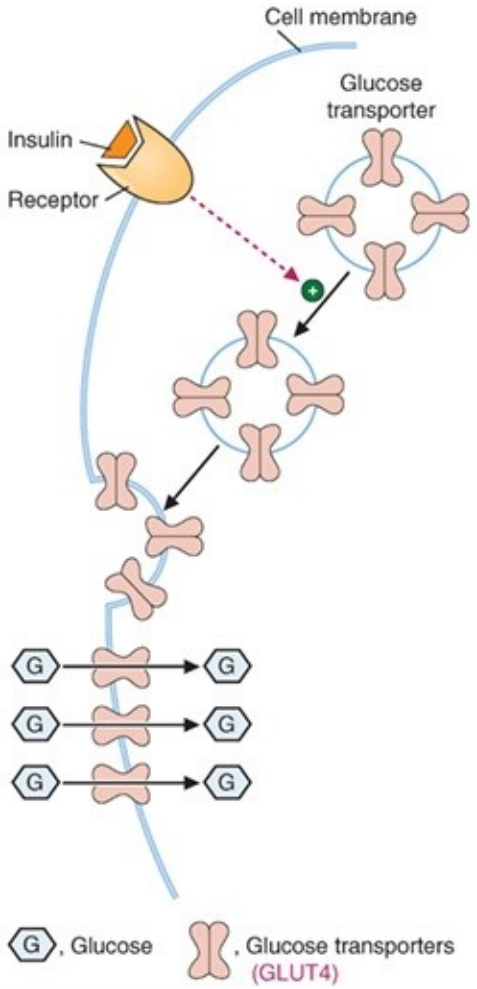


FIGURE 21.8 Stimulation by insulin of glucose transport into muscle and adipose cells. Binding of insulin to its cell membrane receptor causes vesicles containing glucose transport proteins to move from inside the cell to the cell membrane.

V. Glucose Transport through the Blood–Brain Barrier and into Neurons

A hypoglycemic response is elicited by a decrease of blood glucose concentration to some point between 18 and 54 mg/dL (1 and 3 mM). The hypoglycemic response is a result of a decreased supply of glucose to the brain and starts with light-headedness and dizziness and may progress to coma. The slow rate of transport of glucose through the blood–brain barrier (from the blood into the cerebrospinal fluid) at low levels of glucose is thought to be responsible for this neuroglycopenic response. Glucose transport from the cerebrospinal fluid across the plasma membranes of neurons is rapid and is not rate-limiting for ATP generation from glycolysis.

In the brain, the endothelial cells of the capillaries have extremely tight junctions, and glucose must pass from the blood into the extracellular cerebrospinal fluid by GLUT 1 transporters in the endothelial cell membranes (Fig. 21.9) and then through the basement membrane. Measurements of the overall process of glucose transport from the blood into the brain (mediated by GLUT 3 on neural cells) show a $K_{m,app}$ of 7 to 11 mM and a maximal velocity not much greater than the rate of glucose use by the brain. Thus, decreases of blood glucose below the fasting level of 80 to 90 mg/dL (~5 mM) are likely to significantly affect the rate of glucose metabolism in the brain because of reduced glucose transport into the brain.

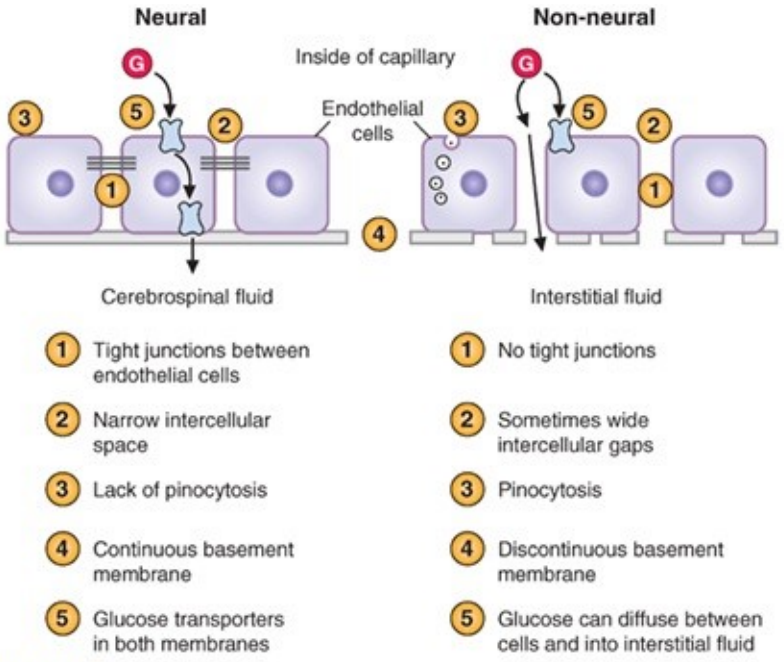


FIGURE 21.9 Glucose transport through the capillary endothelium in neural and non-neural tissues. Characteristics of transport in each type of tissue are listed by numbers that refer to the *numbers* in the drawing. *G*, glucose.

CLINICAL COMMENTS

Denise V. One out of five Americans experiences some form of gastrointestinal discomfort from 30 minutes to 12 hours after ingesting lactose-rich foods. Most become symptomatic when they consume more than 25 g of lactose at one time (e.g., 8 oz of milk or its equivalent). **Denise V.'s** symptoms were caused by her "new" diet in this country, which included a glass of milk in addition to the milk she used on her cereal with breakfast each morning.

Management of lactose intolerance includes a reduction or avoidance of lactose-containing foods, depending on the severity of the deficiency of intestinal lactase. Hard cheeses (cheddar, Swiss, Jarlsberg) are low in lactose and may be tolerated by patients with only moderate lactase deficiency. Yogurt with "live and active cultures" printed on the package contains bacteria that release free lactases when the bacteria are lysed by gastric acid and proteolytic enzymes. The free lactases then digest the lactose. Commercially available milk products that have been hydrolyzed with a lactase enzyme provide a 70% reduction in total lactose content, which may be adequate to prevent digestive symptoms in

mildly affected patients. Tablets and capsules containing lactase are also available and should be taken 30 minutes before meals.

Many adults who have a lactase deficiency develop the ability to ingest small amounts of lactose in dairy products without experiencing symptoms. This adaptation probably involves an increase in the population of colonic bacteria that can cleave lactose and not a recovery or induction of human lactase synthesis. For many individuals, dairy products are the major dietary source of calcium, and their complete elimination from the diet can lead to osteoporosis. Therefore, other dietary sources such as beans, almonds, tofu, turnip greens, kale, and calcium-fortified juices/beverages or calcium supplements should be recommended. Lactose, however, is used as a "filler" or carrying agent in >1,000 prescription and over-the-counter drugs in this country. People with lactose intolerance often unwittingly ingest lactose with their medications.

Deborah S. Patients with poorly controlled diabetes, such as **Deborah S.**, frequently have elevations in serum glucose levels (hyperglycemia). This is often attributable to a lack of circulating, active insulin, which normally stimulates glucose uptake (through the recruitment of GLUT 4 transporters from the endoplasmic reticulum to the plasma membrane) by the peripheral tissues (heart, muscle, and adipose tissue). Without uptake by these tissues, glucose tends to accumulate within the bloodstream, leading to hyperglycemia.

Nina M. The large amount of H_2 produced on fructose ingestion suggested that **Nina M.'s** problem was one of a deficiency in fructose transport into the absorptive cells of the intestinal villi. If fructose were being absorbed properly, the fructose would not have traveled to the colonic bacteria, which metabolized the fructose to generate the hydrogen gas. If there was a concern for deficiencies of the sucrase–isomaltase complex, a jejunal biopsy could be done; it would allow the measurement of lactase, sucrase, maltase, and trehalase activities. Genetic testing for the presence of a mutation in one of these proteins is also becoming available. Although Nina had no sugar in her urine, malabsorption of disaccharides can result in their appearance in the urine if damage to the intestinal mucosal cells allows their passage into the interstitial fluid. When Nina was placed on a diet free of fruit juices and other foods containing fructose, she did well and could tolerate small amounts of pure

sucrose.

More than 50% of the adult population is estimated to be unable to absorb fructose in high doses (50 g), and >10% cannot completely absorb 25 g of fructose. These individuals, like those with other disorders of fructose metabolism, must avoid fruits and other foods that contain high concentrations of fructose.

BIOCHEMICAL COMMENTS

Cholera. Cholera is an acute watery diarrheal disorder caused by the waterborne gram-negative bacterium *Vibrio cholerae*. It is a disease of antiquity; descriptions of epidemics of the disease date to before 500 BC. During epidemics, the infection is spread by large numbers of *Vibrio* that enter water sources from the voluminous liquid stools and contaminate the environment, particularly in areas of extreme poverty where plumbing and modern waste-disposal systems are primitive or nonexistent. **Dennis V.** experienced cholera after eating contaminated shellfish (see Chapter 10).

After being ingested, the *V. cholerae* organisms attach to the brush border of the intestinal epithelium and secrete an exotoxin that binds irreversibly to a specific chemical receptor (G_{M1} ganglioside) on the cell surface. This exotoxin catalyzes an adenosine diphosphate (ADP)-ribosylation reaction that increases adenylate cyclase activity and thus cyclic adenosine monophosphate (cAMP) levels in the enterocyte. As a result, the normal absorption of sodium, anions, and water from the gut lumen into the intestinal cell is markedly diminished. The exotoxin also stimulates the crypt cells to secrete chloride, accompanied by cations and water, from the bloodstream into the lumen of the gut. The resulting loss of solute-rich diarrheal fluid may, in severe cases, exceed 1 L/hour, leading to rapid dehydration and even death.

The therapeutic approach to cholera takes advantage of the fact that the Na^+-dependent transporters for glucose and amino acids are not affected by the cholera exotoxin. As a result, coadministration of glucose and Na^+ by mouth results in the uptake of glucose and Na^+, accompanied by chloride and water, thereby partially correcting the ion deficits and fluid loss. Amino acids and small peptides are also absorbed by Na^+-dependent cotransport involving transport

proteins distinct from the Na^+-dependent glucose transporters. Therefore, addition of protein to the glucose–sodium replacement solution enhances its effectiveness and markedly decreases the severity of the diarrhea. Adjunctive antibiotic therapy also shortens the diarrheal phase of cholera but does not decrease the need for the oral replacement therapy outlined earlier.

KEY CONCEPTS

- The major carbohydrates in the American diet are starch, lactose, and sucrose.
- Starch is a polysaccharide composed of many glucose units linked together through α-1,4- and α-1,6-glycosidic bonds.
- Lactose is a disaccharide composed of glucose and galactose.
- Sucrose is a disaccharide composed of glucose and fructose.
- Digestion converts all dietary carbohydrates to their respective monosaccharides.
- Amylase digests starch; it is found in the saliva and pancreas, which releases it into the lumen of the small intestine.
- Intestinal epithelial cells contain disaccharidases, which cleave lactose, sucrose, and digestion products of starch into monosaccharides.
- Dietary fiber is composed of polysaccharides that cannot be digested by human enzymes.
- Monosaccharides are transported into the absorptive intestinal epithelial cells via active transport systems.
- Monosaccharides released into the blood via the intestinal epithelial cells are recovered by tissues that use facilitative transporters.
- Diseases discussed in this chapter are summarized in Table 21.6.

TABLE 21.6 Diseases Discussed in Chapter 21

DISEASE OR DISORDER	ENVIRONMENTAL OR GENETIC	COMMENTS
Lactose intolerance	Both	Reduced levels of lactase on the intestinal epithelial cell surface lead to reduced lactose digestion in the intestinal lumen, providing substrate for flora in the large intestine. Metabolism of the lactose by these bacteria leads to the generation of organic acids and gases.
Type 2 diabetes	Both	Healthy diets with controlled intake of carbohydrates will be beneficial in managing blood glucose levels.
Fructose malabsorption	Genetic	Inability to absorb fructose in the small intestine, leading to colonic bacteria metabolism of fructose and the generation of organic acids and gases
Cholera	Environmental	Increased cAMP levels in the intestinal epithelial cells lead to inhibition of ion transport and significant water extrusion from the affected cells, leading to severe diarrhea.

REVIEW QUESTIONS—CHAPTER 21

1. The facilitative transporter that is most responsible for transporting fructose from the blood into cells is which one of the following?
   A. GLUT 1
   B. GLUT 2
   C. GLUT 3
   D. GLUT 4
   E. GLUT 5
2. A patient with alcoholism developed pancreatitis that affected his exocrine pancreatic function. He exhibited discomfort after eating a high-carbohydrate meal. The patient most likely had a reduced ability to digest which one of the following?
   A. Starch
   B. Lactose
   C. Fiber
   D. Sucrose
   E. Maltose

3. A man with type 1 diabetes neglects to take his insulin injections while on a weekend vacation. Cells found within which tissue will be most greatly affected by this mistake?
   A. Brain
   B. Liver
   C. Muscle
   D. Red blood cells
   E. Pancreas
4. After digestion of a piece of cake that contains flour, milk, and sucrose as its primary ingredients, the major carbohydrate products that enter the blood are which of the following?
   A. Glucose
   B. Fructose and galactose
   C. Galactose and glucose
   D. Fructose and glucose
   E. Glucose, galactose, and fructose
5. A patient has a genetic defect that causes intestinal epithelial cells to produce disaccharidases of much lower activity than normal. Compared with a normal person, after eating a bowl of oatmeal and milk sweetened with table sugar, this patient will exhibit higher levels of which of the following?
   A. Maltose, sucrose, and lactose in the stool
   B. Starch in the stool
   C. Galactose and fructose in the blood
   D. Glycogen in the muscles
   E. Insulin in the blood
6. The majority of calories in the US diet are derived from carbohydrates, which can contain a variety of glycosidic bonds. Which one of the following carbohydrates contains glucosyl units linked through α-1,6 glycosidic bonds?
   A. Amylose
   B. Amylopectin
   C. Lactose
   D. Sucrose

E. Maltose

7. A patient has increased her dietary fiber intake in an effort to decrease constipation. She has recently noticed abdominal cramping and bloating as well as increased flatulence. Which one of the following best explains why this is happening?
   A. Human enzymes in the small intestine break down the fiber and produce H_2, CO_2, and methane as byproducts.
   B. Bacteria in the small intestine can convert fiber to H_2, CO_2, and methane.
   C. Viruses in the unwashed vegetables convert fiber to H_2, CO_2, and methane.
   D. Bacteria in the colon can convert fiber to H_2, CO_2, and methane.
   E. Human enzymes in the colon can convert fiber to H_2, CO_2, and methane.
8. A newly diagnosed patient with diabetes avoided table sugar because he knew he had "sugar diabetes," but he continued to consume fruits, fruit drinks, milk, honey, and vegetables, with the result being poor diabetic control. The diet the patient was following contained carbohydrate primarily in which form? Choose the one best answer.
   A. Sucrose
   B. Glucose
   C. Fructose
   D. Lactose
   E. Xylulose
9. A 10-year-old patient had 3 days of severe diarrhea after developing a viral gastroenteritis. Now, whenever she drinks milk, she experiences nausea, abdominal pain, and flatulence. She never had this happen before after drinking milk. Which one of the following would be the best advice for this patient?
   A. She should never consume milk products again.
   B. Her children will have lactose deficiency at birth.
   C. Her ability to drink milk should return in a few days.
   D. She has developed viral gastroenteritis again and should receive antibiotics.

E. The cause of the symptoms is a defect in the colon.

10. A runner wanted to "carb load" just before a race, and she wanted to pick something to eat that has a high glycemic index. Which one of the following foods should the runner pick?
    A. Ice cream
    B. Malted milk balls
    C. Oatmeal cookies
    D. Spaghetti
    E. Potato chips

ANSWERS TO REVIEW QUESTIONS

1. **The answer is E.** The GLUT 5 transporter has a much higher affinity for fructose than glucose and is the facilitator of choice for fructose uptake by cells. The other GLUT transporters do not transport fructose to any significant extent.
2. **The answer is A.** The pancreas produces α-amylase, which digests starch in the intestinal lumen. If pancreatic α-amylase cannot enter the lumen because of pancreatitis, the starch will not be digested to a significant extent. (The salivary α-amylase begins the process, but only for the time during which the food is in the mouth, because the acidic conditions of the stomach destroy the salivary activity.) The discomfort arises from the bacteria in the intestine digesting the starch and producing acids and gases. Lactose, sucrose, and maltose are all disaccharides that would be cleaved by the intestinal disaccharidases located on the brush border of the intestinal epithelial cells (thus, B, D, and E are incorrect). These activities might be slightly reduced because the pancreas would also have difficulty excreting bicarbonate to the intestine, and the low pH of the stomach contents might reduce the activity of these enzymes. However, these enzymes are present in excess and will eventually digest the disaccharides. Fiber cannot be digested by human enzymes, so answer C is incorrect.
3. **The answer is C.** Insulin is required to stimulate glucose transport into muscle and fat cells but not into brain, liver, pancreas, or red blood cells.