CHAPTER 2

Nutrients: Ingestion to Energy Metabolism

Key Questions Addressed

- What happens to nutrients after they are ingested?
- How are carbohydrates digested, absorbed, transported, and assimilated in the body?
- How are fats digested, absorbed, transported, and assimilated in the body?
- How are proteins digested, absorbed, transported, and assimilated in the body?
- How are minerals, vitamins, and water absorbed and transported in the body?
- What is energy metabolism, and why is it important?
- What is energy?
- What is the human body's source of chemical energy?
- How do cells make ATP?
- What are the three energy systems?
- How do the energy systems work together to supply ATP during sport performance?
- What metabolic pathways are involved with the energy systems?

You Are the Nutrition Coach

Kay is an aspiring 800-meter track athlete who has read various nutrition books with the hope of finding the ideal diet for her sport. From her reading, she has learned that fats yield more calories per gram than carbohydrates. In addition, she knows that dietary proteins are needed to help her muscles recover from training and additionally can be used for energy. She is now convinced that one of the popular high-fat, high-protein, low-carbohydrate diets is her best choice. Her coach disagrees with her decision. She recommends that Kay speak with a sports nutrition professional prior to changing her current diet, in which the majority of calories come from carbohydrates.

Questions

- Bioenergetically speaking, is Kay on the right track with her thinking?
- What energy system does an athlete running the 800-meter event rely on for energy?
- Is a diet of energy-dense fats really better for Kay's event?
- How would you explain to Kay why she should or should not follow this new diet?

What happens to nutrients after they are ingested?

When nutrients are ingested they have not technically entered the body. The digestive tract is merely an internalized conduit that connects the mouth to the anus (see Figure 2.1). Substances in the digestive tract are technically still outside of the body until they are absorbed across the membrane linings of this system. Once absorbed across the membranes of the digestive tract, the nutrients have officially entered the body and can be transported via blood and lymph throughout the body. Because most foods are too large to be absorbed, they first must be broken down into smaller pieces via digestion.

Digestion is the process of breaking down ingested food through mechanical and enzymatic activity so that it can be absorbed into the body. The remainder of this section will discuss the various parts of the gastrointestinal system and their function in nutrient digestion and absorption.

digestion The process of breaking down ingested foods into their basic units in preparation for absorption by the cells of the gastrointestinal tract.

oral cavity Another name for the mouth, which makes up the first segment of the gastrointestinal tract.

mastication The process of chewing.

salivary glands Glands of the mouth that produce and secrete saliva.

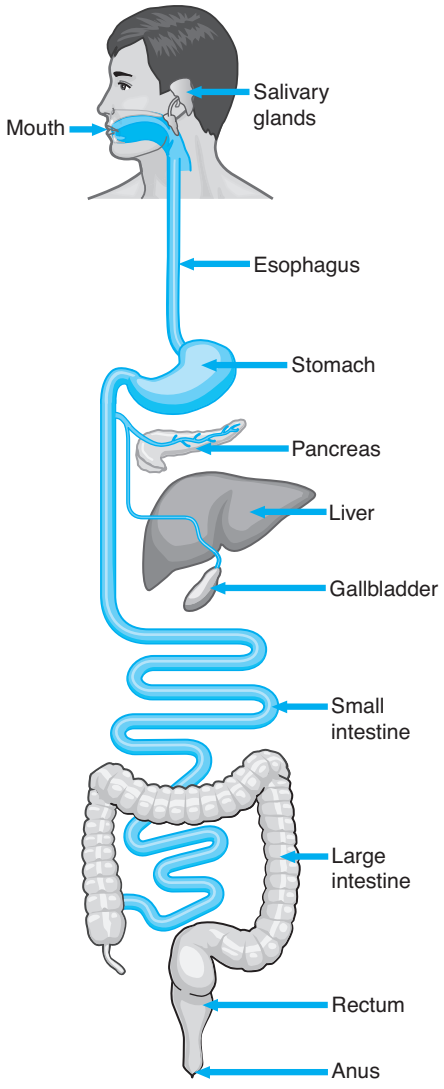

Figure 2.1 Anatomy of the digestive system.

What are the functions of the various parts of the digestive system?

The anatomical organization and functions of the various parts of the digestive tract are shown in Figure 2.2. The digestive system extends from the mouth to the anus and is more than 25 feet long in most individuals. The mouth, or oral cavity, is the entry point for ingested nutrients. The main digestive process that occurs in the mouth is mastication, more commonly known as "chewing." The mechanical process of mastication breaks foods into pieces, thereby increasing the exposed surface area of the food and facilitating enzymatic action. Three pairs of salivary glands, namely the parotid, submandibular, and sublingual glands,

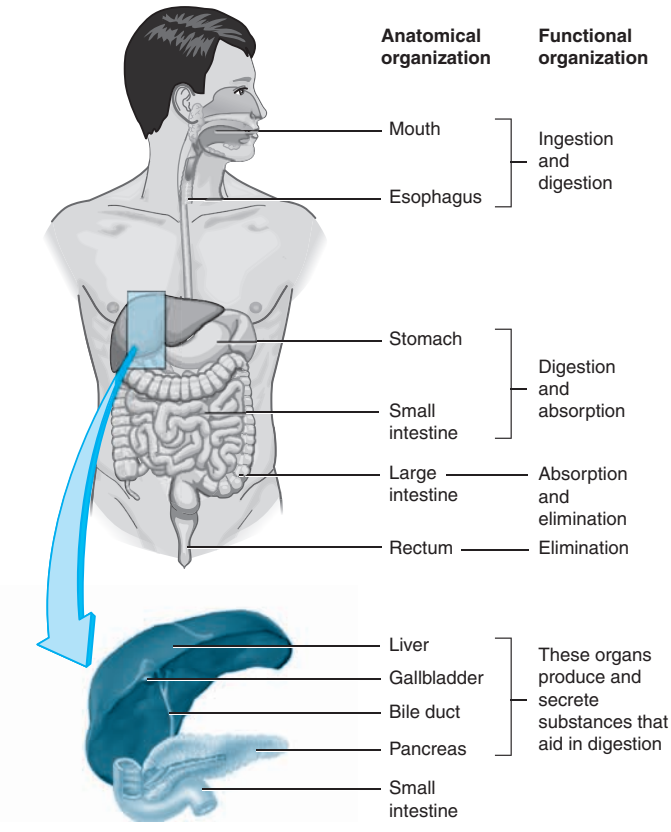

Figure 2.2 Functional organization of the digestive system. Although digestion begins in the mouth, most digestion occurs in the stomach and small intestine. Absorption occurs primarily in the small intestine.

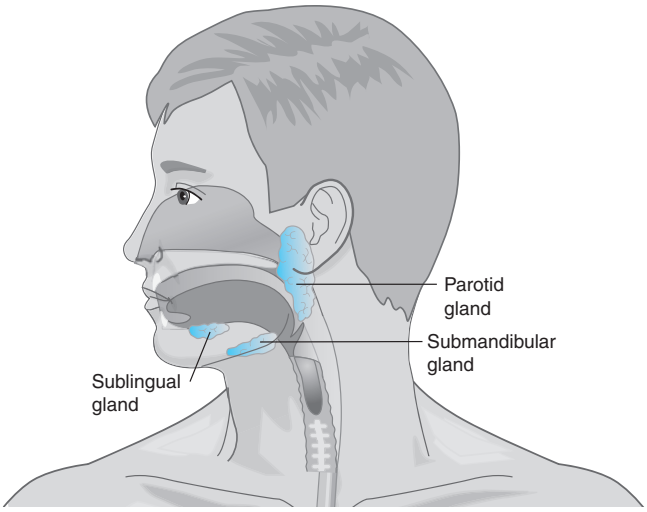

Figure 2.3 The salivary glands. The three pairs of salivary glands supply saliva, which moistens and lubricates food. Saliva also contains salivary enzymes that begin the digestion of starch.

secrete saliva into the oral cavity (see Figure 2.3). The saliva not only moistens the food particles, but also contains enzymes that initiate the enzymatic breakdown of carbohydrates and fats.

The bolus of food is then swallowed and passes into the **esophagus**, which is a tube leading from the back of the oral cavity to the **stomach**. Food passes so quickly through the esophagus that relatively little digestion occurs there. Once in the stomach, the food is subjected to stomach acids and other enzymes that further the digestive process. The stomach has a muscular wall that churns the food, mixing it with stomach acids and enzymes. This digestive process continues for roughly an hour before food begins to exit the stomach. Although some absorption of nutrients does occur in the stomach, the overwhelming majority occurs in the next portion of the **gastrointestinal tract (GI tract)**, the **small intestine**.

esophagus The segment of the digestive system that connects the oral cavity to the stomach.

stomach The distensible, pouch-like portion of the gastrointestinal system that receives foods from the esophagus. It has muscular walls that mechanically churn food and assist in the digestive process. Ingested foods pass from the stomach into the duodenum.

gastrointestinal tract (GI tract) The regions of the digestive system that include the stomach, small intestine, and large intestine.

small intestine The portion of the gastrointestinal system where the bulk of digestion and absorption occurs. The small intestine is divided into three segments: duodenum, jejunum, and ileum.

The small intestine makes up the majority of the length of the GI tract and is approximately 20 feet long. It is divided into three segments: the duodenum, the jejunum, and the ileum (see Figure 2.4). As the partially digested food exits the stomach, it enters the duodenum, which is a short segment of the small intestine. Although approximately only a foot in length, the duodenum is where the food from the stomach is barraged with more digestive enzymes from the gallbladder and pancreas. Much of the digestion of foodstuffs is completed in the duodenum, making the food ready for absorption.

In addition to the small intestine being long, the walls inside it are convoluted and lined with **villi**, which are small tube-shaped projections (see Figure 2.5). Each villus has blood and lymphatic supply so that absorbed nutrients can gain easy access into the circulatory systems of the body. The combination of the small intestine's length and the convoluted villi-lined interior results in a large surface area with which to absorb foodstuff. In fact, most of the absorption of nutrients occurs in the remaining segments of the small intestine: the jejunum and ileum.

villi Small rod-shaped projections that cover the walls of the small intestine.

large intestine The terminal portion of the gastrointestinal tract, which receives undigested, partially digested, and unabsorbed contents from the small intestine. It is in the large intestine that the formation of feces occurs. The large intestine consists of the colon, rectum, and anal canal.

defecation The physical process of excreting feces from the rectum.

From the small intestine, the remainder of the undigested, partially digested, and unabsorbed contents pass into the **large intestine**. The large intestine includes the colon (ascending, transverse, and descending), the rectum, and the anal canal, which exits the body at the anus (see Figure 2.6). Passage of the intestinal contents along the GI tract slows in the large intestine, normally taking 18 to 24 hours to pass through. The intestinal contents are subjected to bacteria that not only continue digesting some of the undigested and unabsorbed foodstuffs, but also produce intestinal gas and certain vitamins. Some of the vitamins produced by these bacteria are absorbed along with excess water as the remaining contents pass through the colon. Water absorption in the colon helps to solidify the remaining excrement, which by the time it reaches the rectum is 60% solid matter and 40% water. The rectum is basically the storage site for the excrement until elimination, or **defecation**, occurs. The following sections will provide a more detailed explanation of how and where each nutrient is digested and absorbed.

How are carbohydrates digested, absorbed, transported, and assimilated in the body?

Many different types of carbohydrates are found in foods. The commonality regarding the different

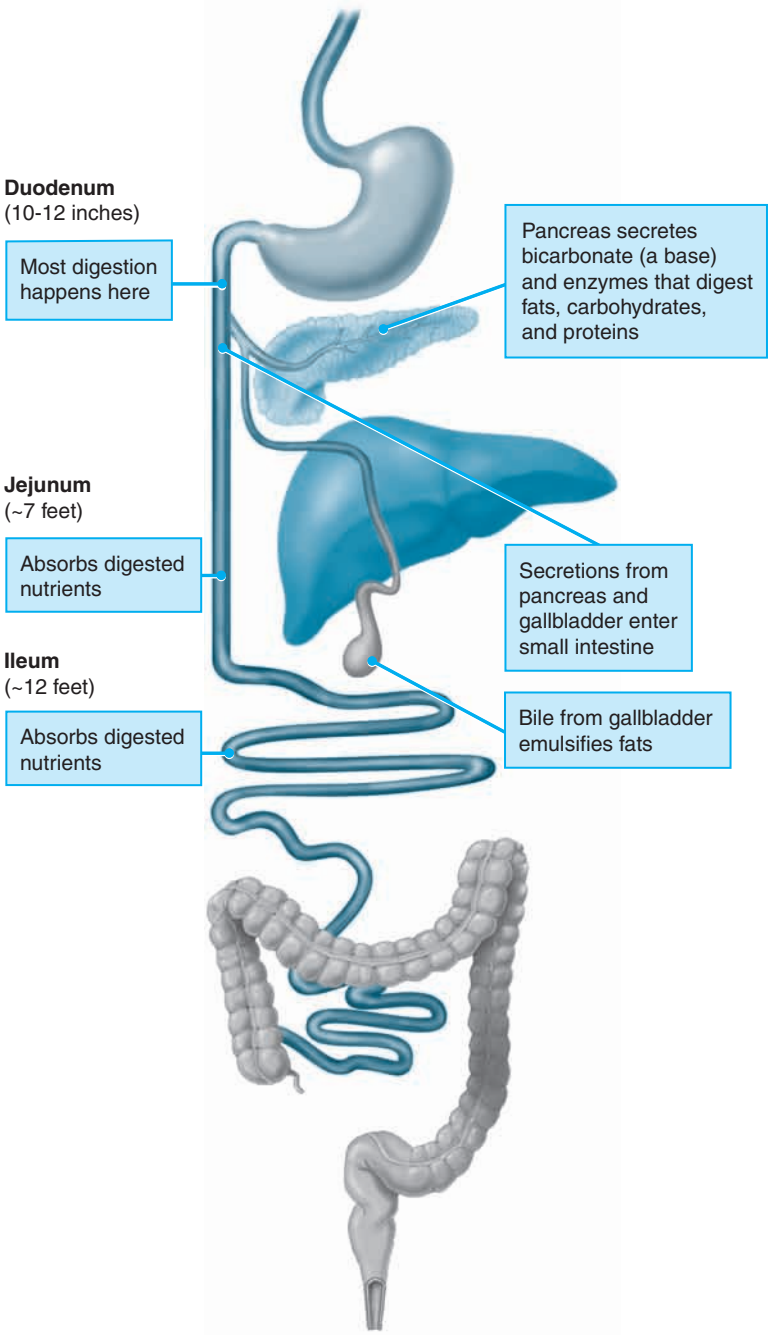

Figure 2.4 The small intestine. Secretions from the pancreas, liver, and gallbladder assist in digestion. All along the intestinal walls, nutrients are absorbed into blood and lymph. Undigested materials are passed on to the large intestine.

types of carbohydrates is that they are all composed of simple sugars known as monosaccharides. Carbohydrates are classified based on the number of simple sugars making up their structure. For example, disaccharides are made up of two linked simple sugars. Oligosaccharides are carbohydrates composed of 3 to 10 linked sugars, and polysaccharides are complex carbohydrates made of 11 or more linked simple sugars. The monosaccharide most important to the human body is glucose. To obtain glucose from ingested foods, the carbohydrates must undergo digestion. The digestive process breaks down the carbohydrates into their constituent sugars so that they can be absorbed, transported, and used by the cells of the body.

monosaccharide A single sugar molecule. Monosaccharides are the building blocks for more complex carbohydrates.

disaccharide A simple carbohydrate that consists of two linked sugar molecules.

What happens to carbohydrates once they are put into the mouth?

The digestive process begins with the mechanical actions of mastication and the activity of an enzyme found in the saliva secreted by the salivary glands. Saliva contains the enzyme amylase, which begins the breakdown of starchy foods to individual glucose molecules. Starch is the only type of carbohydrate and, besides fats, the only nutrient in which enzymatic breakdown begins in the mouth. Although digestion starts in the mouth, very little of the starch is completely broken down to glucose by the time the food is swallowed and enters the esophagus. In the short transit time through the esophagus to the stomach, amylase continues its breakdown of starch.

Once in the stomach, the food is subjected to hydrochloric acid, which denatures the salivary amylase, thus halting enzymatic digestion of starches in the stomach. However, the mechanical breakdown of food continues through the churning and powerful contractions of the smooth muscle in the stomach walls. The smooth muscle actions help to mix the stomach acid into the food bolus. This process, which prepares the food bolus for movement into the small intestine, usually takes 1 to 4 hours. No absorption of carbohydrates or other nutrients, except for alcohol, occurs in the stomach (see Figure 2.7); these nutrients therefore pass on with the other gastric contents into the small intestine.

oligosaccharide A complex carbohydrate made up of 3 to 10 linked simple sugars.

polysaccharide A complex carbohydrate composed of 11 or more linked simple sugars. Starches and glycogen are examples of polysaccharides.

amylase A digestive enzyme that breaks down carbohydrates into simple sugars.

starch The major plant storage form of carbohydrates. Starch is composed of long chains of linked glucose molecules.

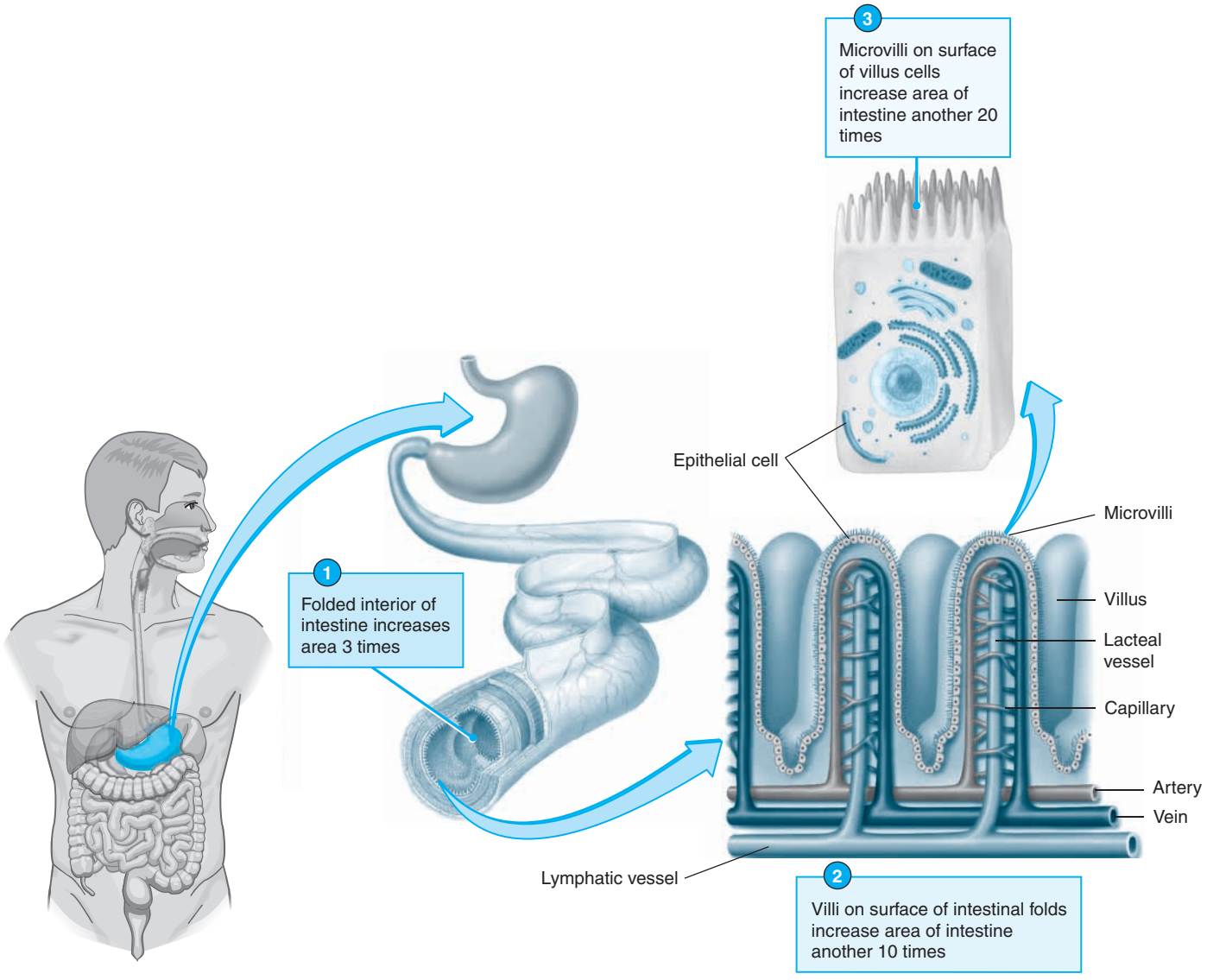

Figure 2.5 The absorptive surface of the small intestine. To maximize the absorptive surface area, the small intestine is folded and lined with villi. You have a surface area the size of a tennis court packed into your gut.

pancreatic amylase An enzyme secreted by the pancreas into the duodenum that assists in the digestion of starches.

brush border disaccharidases Digestive enzymes produced by cells of the intestinal wall that break disaccharides into simple sugars.

The small intestine is where the majority of digestion and absorption of carbohydrates and other nutrients occurs. In the duodenum, the bolus of food is exposed to digestive enzymes from the pancreas, gallbladder, and cells of the small intestine (see Figure 2.4). The pancreas secretes **pancreatic amylase**. This enzyme continues the digestion of starch, breaking it down into the disaccharide maltose. The mucosal cells and microvilli of the intestinal tract contain their own enzymes called the **brush border disaccharidases**. These enzymes go to work on the food as it enters the small intestine

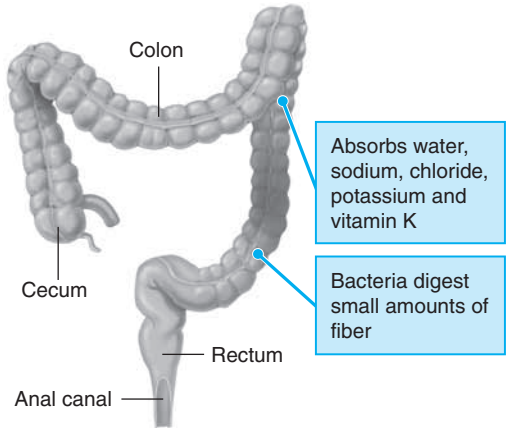

Figure 2.6 The large intestine. In the large intestine, bacteria break down dietary fiber and other undigested carbohydrates, releasing acids and gas. The large intestine absorbs water and minerals and forms feces for excretion.

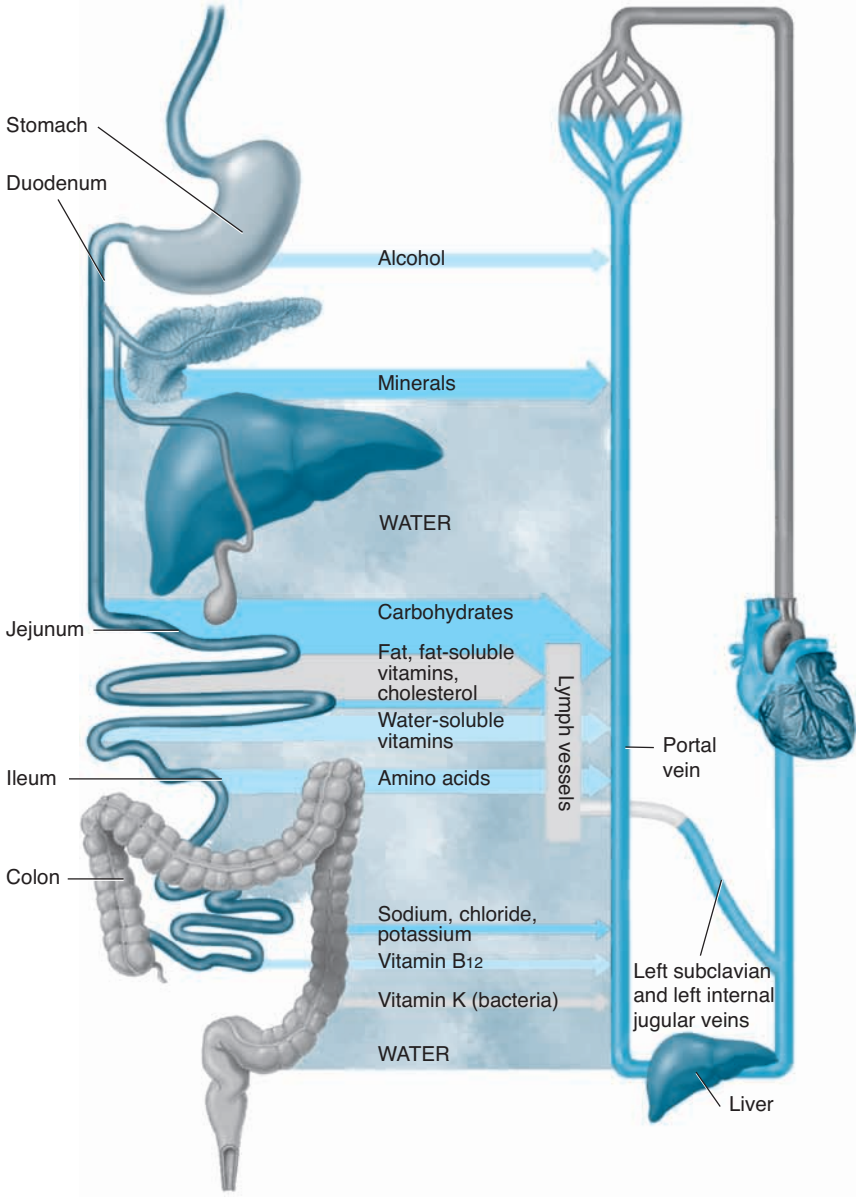

Figure 2.7 Absorption of nutrients.

maltase A digestive enzyme that breaks down maltose into two glucose molecules.

sucrase A digestive enzyme that breaks down sucrose into glucose and fructose molecules.

lactase A digestive enzyme that breaks lactose into the simple sugars galactose and glucose.

and break down disaccharides into monosaccharides, which are then ready for absorption. There are a variety of disaccharidases that function to digest specific carbohydrates. For example, **maltase** splits the disaccharide maltose into two single glucose molecules. **Sucrase** splits sucrose into glucose and fructose. **Lactase** splits lactose into glucose and galactose. After enzymatic digestion of the carbohydrates, the resulting simple sugars are absorbed through the intestinal wall in the jejunum and upper ileum (see Figure 2.7) and enter the bloodstream.

When individuals have an insufficient supply of the enzyme lactase in their intestinal tract, they are not able to break down the milk sugar lactose. As a result, lactose goes undigested and is passed on to the large intestine, where it is exposed to bacteria. The bacteria ferment lactose in the colon, producing gas and bloating. Consuming dairy products that have added lactase or taking products like Lactaid prior to consumption of dairy foods can decrease or eliminate these symptoms.

Any unabsorbed and/or undigested polysaccharides, such as fiber, that make it through the small intestine enter into the large intestine, where some bacterial digestion and gas formation can occur. However, no absorption of carbohydrates

occurs in the large intestine, and thus any remaining carbohydrates pass through the system and are eliminated as feces. Figure 2.7 provides a graphic summary of nutrient absorption, showing that the majority of carbohydrates are absorbed in the jejunum.

How are the simple sugars absorbed into the intestinal wall?

There are four ways that nutrients can be absorbed into the intestines: passive diffusion, facilitated diffusion, active transport, and endocytosis (see Figure 2.8). The following is a brief overview of how

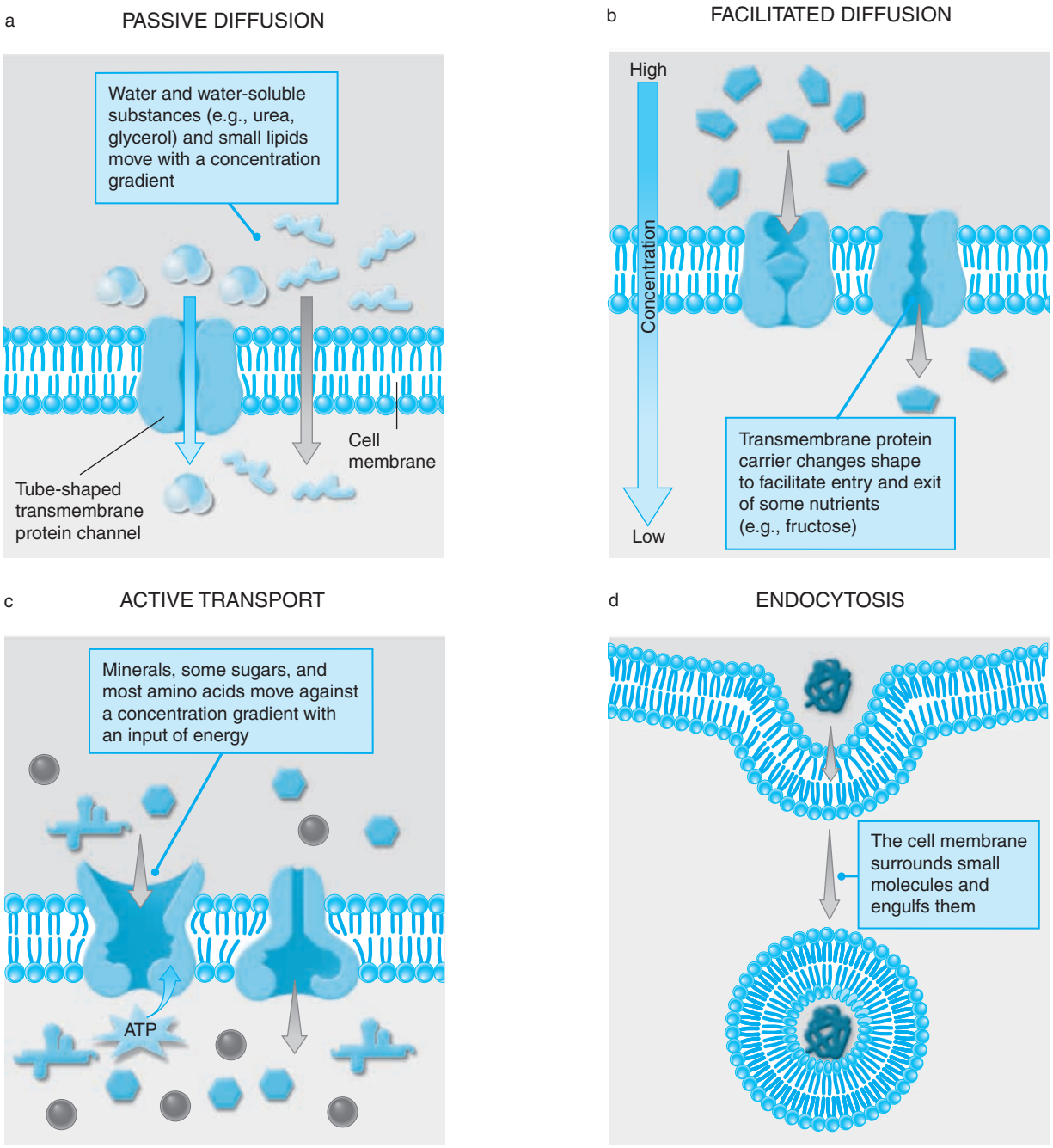

Figure 2.8 Mechanisms for nutrient absorption. (a) Passive diffusion. Using passive diffusion, some substances easily move in and out of cells, either through protein channels or directly through the cell membrane. (b) Facilitated diffusion. Some substances need a little assistance to enter and exit cells. The transmembrane protein helps out by changing shape. (c) Active transport. Some substances need a lot of assistance to enter cells. Similar to swimming upstream, energy is needed for the substance to penetrate against an unfavorable concentration gradient. (d) Endocytosis. Cells can use their cell membranes to engulf a particle and bring it inside the cell. The engulfing portion of the membrane separates from the cell wall and encases the particle in a vesicle.

passive diffusion A means of cellular absorption in which the movement of molecules through permeable cell membranes is driven only by differences in concentration gradient.

facilitated diffusion A means of cellular absorption in which protein carrier molecules are required to move substances across membranes driven only by differences in concentration gradient.

active transport An energy-requiring means of cellular absorption in which substances are carried across membranes by protein molecules. Active transport is not dependent on concentration gradients.

these absorptive processes are used for carbohydrates.

Passive diffusion involves the movement of molecules through permeable cell membranes driven only by differences in concentration gradient. Passive diffusion is a non-energy-requiring mechanism of absorption, and molecules always move from high concentration to low concentration. The bigger the difference in concentration, the greater the movement of molecules across the membrane. Molecules can enter cells by passively diffusing through the cell membrane or by passing through protein channels in the cell membrane (see Figure 2.8a). Because cell membranes are composed of fatty substances, fats and fat-soluble molecules, such as oxygen, carbon dioxide, and alcohol, can pass directly through membranes during passive diffusion. Conversely, water passively diffuses across membranes using the protein channels in the cell membranes. Unlike water, the water-soluble nutrients, such as carbohydrates, amino acids, minerals, and some vitamins, are not absorbed via passive diffusion and must rely on another form of transport, known as facilitated diffusion.

Facilitated diffusion, similar to passive diffusion, does not require energy, and molecules move from areas of high concentration to low concentration; however, molecules must be carried across the membrane by protein carriers (see Figure 2.8b). The monosaccharide fructose is absorbed via facilitated diffusion, but because its passage through membranes is dependent solely on concentration gradients, its absorption is slower than that of other monosaccharides, such as glucose and galactose, which are absorbed by active transport.

Active transport is an energy-requiring form of absorption that requires transporter proteins, but, unlike facilitated diffusion, the direction of the transport is not dictated by concentration gradients (see Figure 2.8c). In other words, during active transport molecules can be moved against concentration gradients (i.e., from low to high concentrations). The monosaccharides glucose and galactose are absorbed across the intestinal lining via active transport. The name of the transporter protein found in the intestines is SGLUT1. For SGLUT1 to transport these simple sugars through the intestinal cell membrane, it must first bind to a sodium ion. Conversely, if no sugars are available, the bound sodium is not transported into the cell either. In other words, SGLUT1 must bind both a sodium ion and sugar for transport into the cell to occur. This is the reason why physiology books refer to this specific active transport process as a glucose–sodium symport.

Endocytosis is a means of cellular uptake that involves the cell membrane encircling molecules and internalizing them (see Figure 2.8d). Although the process of endocytosis does occur in cells lining the GI tract, it is not a process that accounts for carbohydrate uptake.

Of the four mechanisms, facilitated diffusion and active transport explain carbohydrate absorption by the cells lining the small intestine.

endocytosis A means of cellular absorption in which substances are encircled by the cell membrane and internalized into the cell.

glycogen The storage form of carbohydrates in animal cells. Glycogen consists of intricately branched chains of linked glucose molecules.

insulin A hormone secreted by specialized cells within the pancreas that lowers blood glucose levels after snacking or meals.

beta cells Specialized cells within the pancreas that secrete the hormone insulin.

diabetes A medical disease that is characterized by high blood glucose levels. Diabetes results when either the beta cells of the pancreas do not produce enough insulin or the body's tissues do not respond normally to insulin when it is produced.

What happens to carbohydrates once they make it into the blood?

Once the simple sugar molecules cross the intestinal cell membranes and enter the blood, they are transported to the liver via the hepatic portal system. This system is a network of blood vessels that collects the absorbed nutrients from the small and large intestines and delivers them to the liver (see Figure 2.7). No special carrier proteins are required when the sugars reach the bloodstream because they are soluble in water (i.e., blood plasma). Once the bloodborne simple sugars reach the cells of the liver, those that are not in the form of glucose (e.g., fructose, galactose) are converted to glucose. The glucose can then be stored as glycogen in the liver cells or released into the bloodstream.

Rising blood glucose levels after ingestion of carbohydrates stimulates the release of insulin, which is a hormone secreted by specialized cells within the pancreas known as beta cells. The release of insulin into the bloodstream causes glucose transporter proteins (see next section) within the cell membranes of muscles and other tissues to begin the uptake of glucose, thereby preventing blood glucose levels from rising too high. Diabetes results when the beta cells

do not produce enough insulin to lower blood glucose levels, or the beta cells produce insulin, to which the body's tissues do not respond normally. The end result is abnormally high blood glucose levels, sometimes in excess of two to four times the normal level.

What happens to carbohydrates once they make it to the cells of the body?

Once glucose is transported to various bodily tissues, such as skeletal muscle, it must gain access to the inside of tissue cells in order to be used for energy or to be stored. Unlike in intestinal absorption where glucose is actively transported via SGLUT1, glucose in the blood is taken up by cells by specialized transporter proteins via facilitated diffusion. These specialized membrane proteins are called **glucose transporters (GLUT)** and are present in all cells in the body. Some of these glucose transporters are stimulated by the hormone insulin, which, in turn, increases the rate of cellular glucose uptake.

glucose transporters (GLUT) Specialized membrane carrier proteins that are responsible for the active transport of glucose into muscle cells.

Several different types of glucose transporters are present in various tissues throughout the body. In regard to muscle, the transporters are called GLUT1 and GLUT4. At rest or when blood levels of the hormone insulin are low, most glucose enters muscle cells via the GLUT1 transporter. However, when glucose and insulin levels in the blood are high (e.g., after a meal) or when muscle is active (e.g., during exercise), the GLUT4 transporter protein is stimulated and becomes the major transporter of glucose into the muscle cells. Once the glucose has gained entrance into the cell, it basically has one of three fates. It can be stored as glycogen in the muscle, it can be converted into fat and stored as adipose tissue, or it can be used for energy (see Figure 2.9).

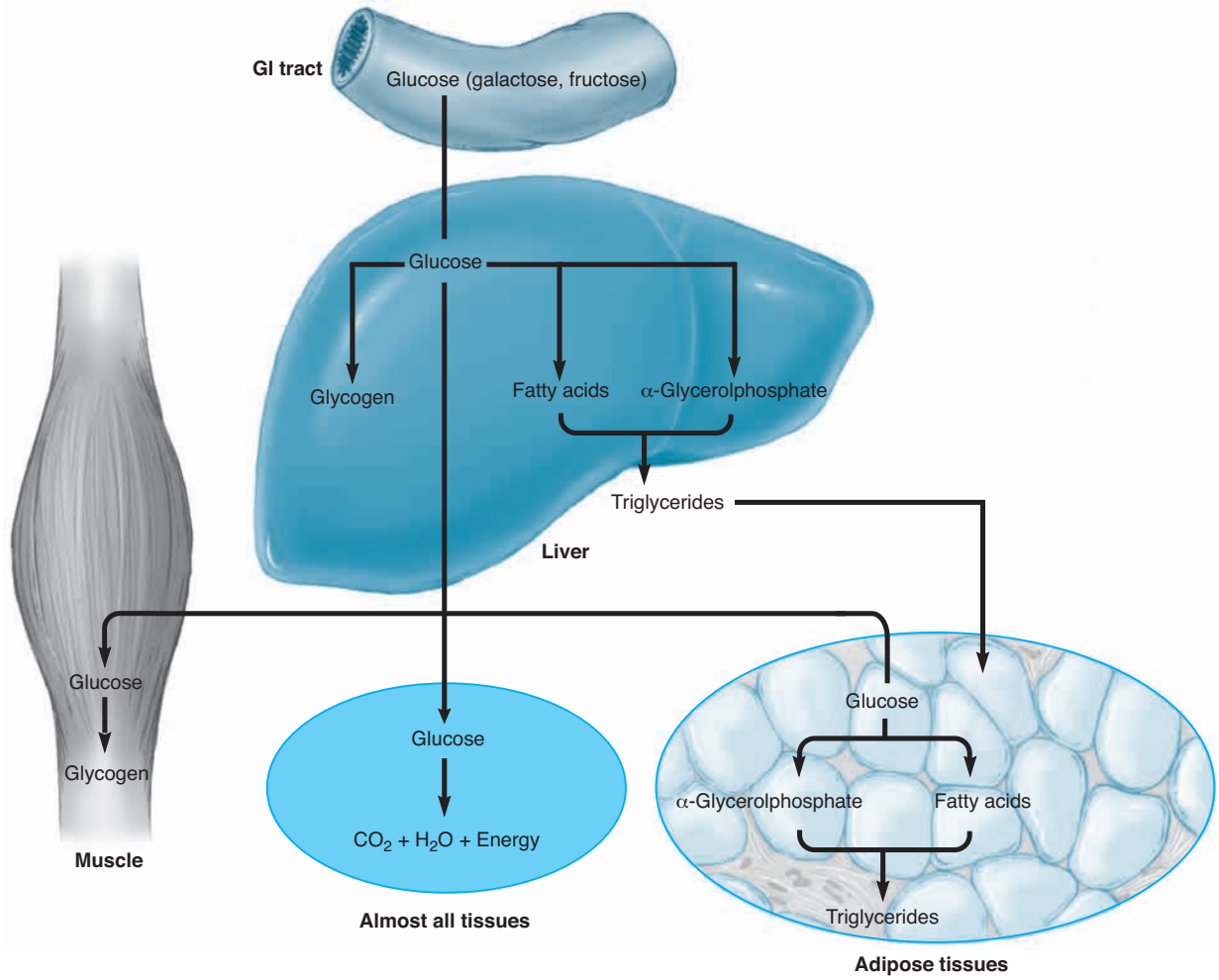

Figure 2.9 Flowchart of glucose and other simple sugars immediately after a meal.
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If it is stored, the glucose molecule can be linked to other glucose molecules, forming the complex carbohydrate known as glycogen. Glucose can remain stored as glycogen in the cell until needed for energy, at which point it is cleaved from the glycogen chain and metabolized for energy.

How are fats digested, absorbed, transported, and assimilated in the body?

Although fats are made up of carbon, hydrogen, and oxygen atoms similar to carbohydrates, they have very different chemical structures and physical properties. Fats are molecules that belong to a group of compounds known as lipids, which are organic compounds that are insoluble in water and feel greasy to the touch. Sources of dietary lipids are butter, margarines, salad dressings, and oils. Lipids are also found in meats, dairy products, nuts, seeds, olives, avocados, and some grain products. Most dietary lipids exist in the form of triglycerides; therefore, the following discussion will focus on the digestion, absorption, transport, and assimilation of triglycerides (see Figure 2.10).

lipids A class of organic compounds that is insoluble in water and greasy to the touch. Lipids are commonly referred to as fats and exist in the body primarily as triglycerides.

triglyceride A lipid that is composed of a glycerol molecule with three attached fatty acids.

Fatty acids are basically carbon atoms that are linked in a chainlike fashion (see Figure 2.11). These chains of carbon can be of varying lengths, and thus fatty acids can be classified as short (4 or fewer carbons), medium (6 to 10 carbons), or long (12 or more carbons). During triglyceride digestion, one fatty acid may be removed, leaving a diglyceride, or two fatty acids may be removed, leaving a monoglyceride. The fatty acids cleaved off the glycerol backbone become what are known as free fatty acids.

diglyceride A lipid that is composed of a glycerol molecule with two attached fatty acids.

monoglyceride A lipid composed of a glycerol molecule with one attached fatty acid.

free fatty acid Compounds composed of long hydrogen-carbon chains that have a carboxyl group on one end and a methyl group at the other. Free fatty acids can be formed when a fatty acid is cleaved from a triglyceride molecule.

emulsifier A substance that breaks lipids into very small globules so that they are more manageable in watery fluids.

lingual lipase An enzyme for fat digestion that is secreted by cells located at the base of the tongue.

gastric lipase A fat-digesting enzyme secreted by cells of the stomach.

Fat digestion, absorption, and transport are more elaborate than that of other macronutrients because of fat's insolubility in water. For example, the majority of enzymes involved in digestion are water soluble, which under normal circumstances would prohibit them from effectively acting on fats. However, the body's digestive system subjects fats to substances known as emulsifiers, which work around the insolubility issue and allow enzymes to do their job. Emulsifiers are substances that break lipids into very small globules that stay suspended in the watery contents of the GI tract and increase the exposed surface area of fats to the actions of digestive enzymes. Without being emulsified, the fats would tend to stick together in large clumps, making it difficult for enzymes to do their jobs. As noted earlier, the following discussion focuses on the digestion of triglycerides.

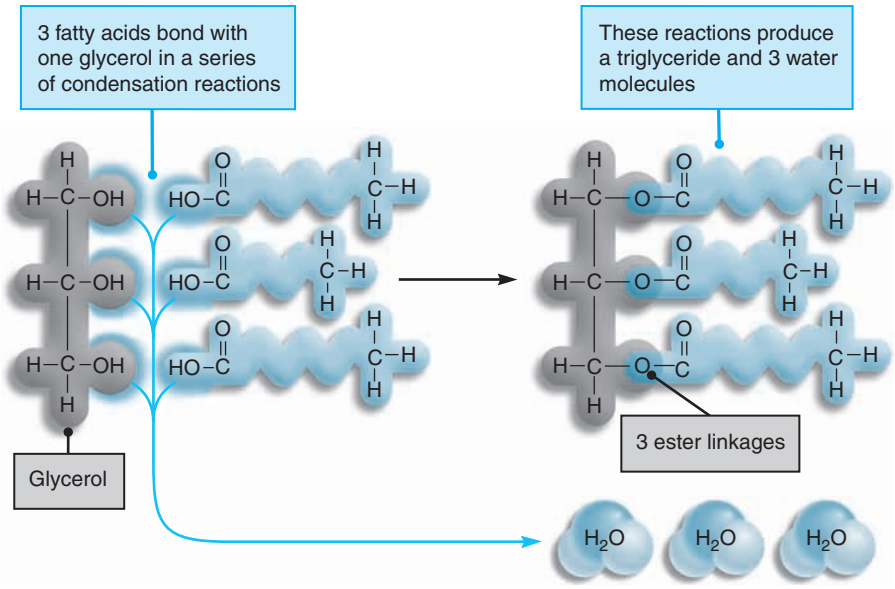


Figure 2.10 Forming a triglyceride. Concentration reactions attach three fatty acids to a glycerol backbone to form a triglyceride. These reactions release water.

What happens to fats once they are put into the mouth?

Mastication breaks up fat into smaller pieces, and lingual lipase in saliva initiates the enzymatic digestive process. However, because food is in the mouth for a relatively short period of time before being swallowed, very little fat is actually digested in the mouth.

When food is swallowed, the lingual lipase is passed into the stomach, where it continues to break down the fats, at least until it is denatured by stomach acid. Gastric lipase is secreted by the chief cells in the stomach lining

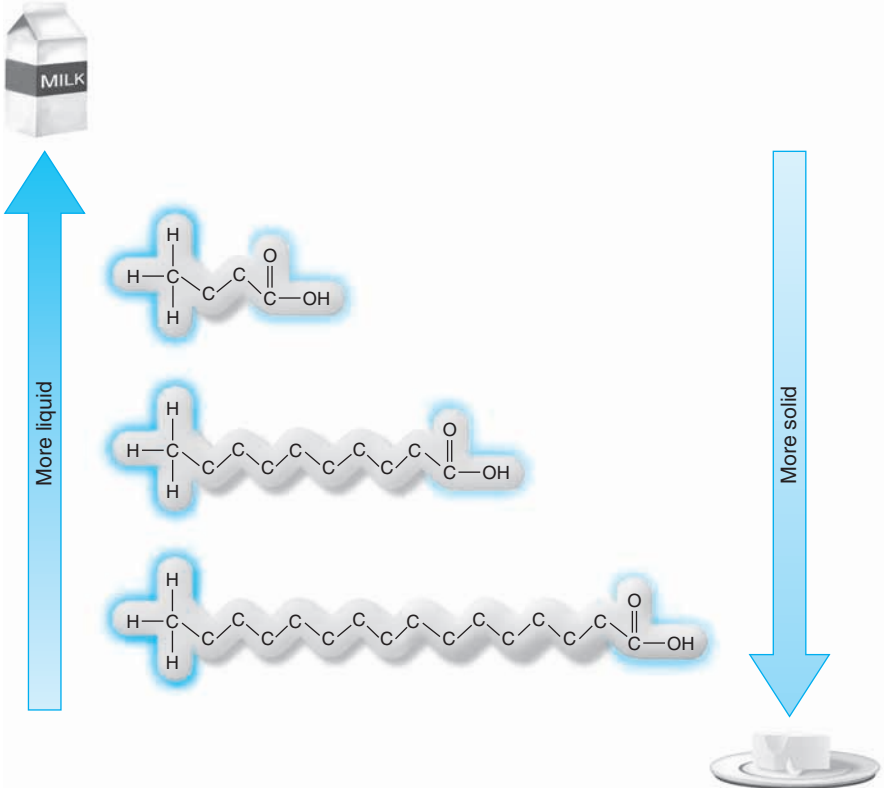


Figure 2.11 Fatty acids vary in length and can be classified as short, medium, or long. The longer the fatty acid, the more solid it is at room temperature.

and continues the enzymatic digestive process in the stomach. The gastric lipase breaks the triglycerides into diglycerides, which aid in the digestive process by serving as emulsifiers. Churning and muscular contractions of the muscles in the stomach wall also assist in breaking apart large pieces of food and, in combination with emulsifiers, help keep the fats dispersed and in suspension. After 2 to 4 hours in the stomach, approximately one-third of the dietary triglycerides have been broken down into diglycerides and free fatty acids.[1]

As the food contents reach the small intestine, they stimulate the duodenal cells to release hormones that further assist in digestion. Cholecystokinin (CCK) is released and travels to the gallbladder. The CCK stimulates the gallbladder to contract, forcing bile into the bile duct, which empties into the duodenum (see Figure 2.2). Bile is important in the fat digestion process because it contains bile salts and lecithin (a type of lipid), which keep the fats emulsified so that the water-soluble digestive enzymes can continue to do their job. Secretin, released from duodenal cells, stimulates the pancreas to release bicarbonate, which neutralizes the acidity of the intestinal contents. Neutralizing the acids prevents denaturation of protein enzymes, such as pancreatic lipase and other digestive enzymes, allowing the enzymatic breakdown of foods to progress. The pancreatic lipase is released in large amounts and finishes the digestive process of fats, thereby breaking the remaining triglycerides into glycerol, monoglycerides, and free fatty acids of various lengths. Short- and medium-chain fatty acids, which are water soluble, are absorbed into the intestinal lining via passive diffusion. The monoglycerides and long-chain fatty acids, which are water insoluble, are encircled by bile salts, forming microscopic bubbles known as micelles. The micelles transport the long-chain fatty acids and monoglycerides to the cells lining the intestinal walls, at which time they are released from the micelles and passively diffused into the interior of the intestinal cells. Figure 2.12 provides a graphic summary of triglyceride digestion.

cholecystokinin (CCK) A hormone produced by cells of the small intestine that stimulates the release of bile salts and pancreatic enzymes.

secretin A hormone released from the duodenum that stimulates the release of bicarbonate from the pancreas.

pancreatic lipase A digestive enzyme secreted by the pancreas into the duodenum that breaks down triglycerides.

micelles Tiny bubbles made up of monoglycerides and long-chain fatty acids that are wrapped in bile salts. Micelles help transport digested fats to the intestinal wall for absorption.

steatorrhea An abnormal condition in which large amounts of fat are found in the feces.

Fat digestion and absorption are for the most part completed by the time the food contents reach the large intestine. Minimal amounts of fat are found in the large intestine or passed in fecal matter. However, some disease conditions can cause fat malabsorption, resulting in steatorrhea, or fatty stools. Radiation therapy for cancer, digestive surgeries requiring a large portion of the small intestine to be removed, Crohn's disease, and cystic fibrosis all can cause fat malabsorption.

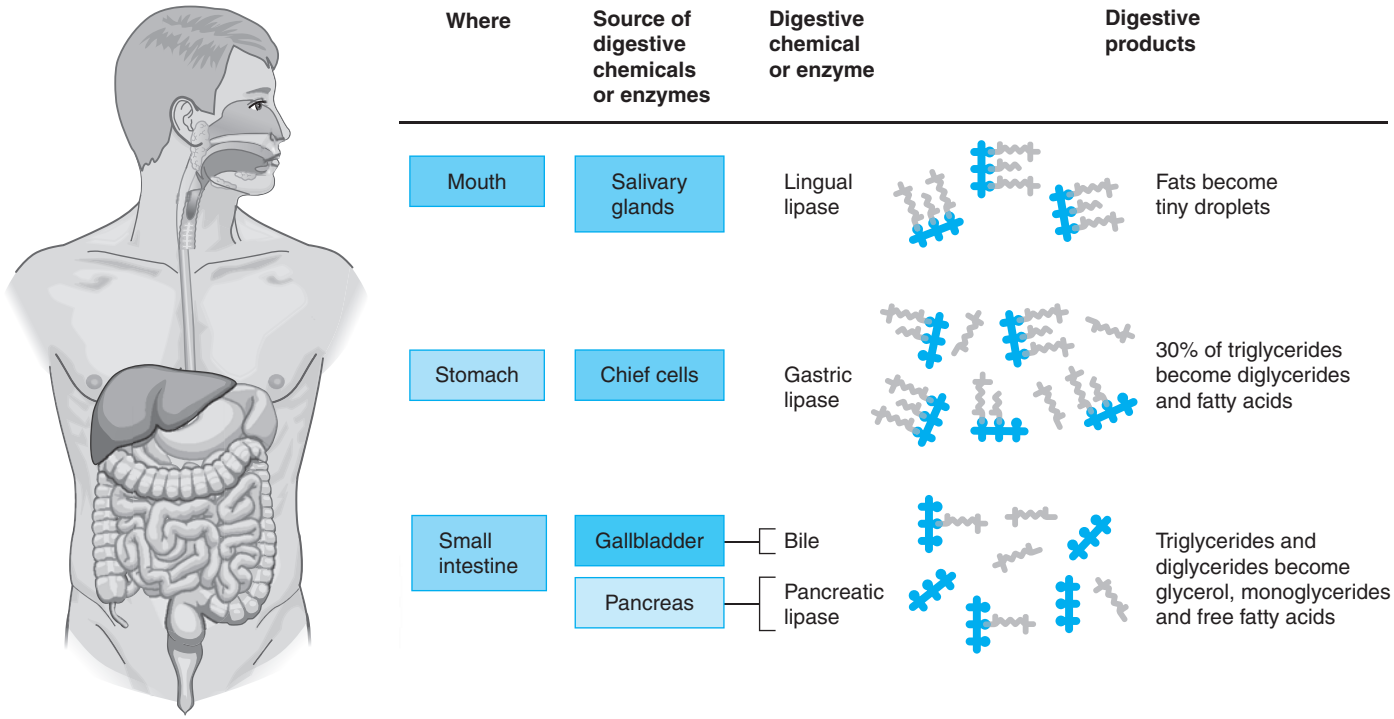


Figure 2.12 Triglyceride digestion. Most triglyceride digestion takes place in the small intestine.

What happens to the fats once they are absorbed?

Once absorbed, the water-soluble glycerol and short- and medium-chain fatty acids pass through the intestinal cells and diffuse into capillaries, thus entering directly into the bloodstream (see Figure 2.13). The monoglycerides and long-chain fatty acids that are absorbed are reassembled into triglycerides within the intestinal cells. The resynthesized triglycerides are then combined with protein carriers to form **lipoproteins**. These lipoproteins with their fatty cargo then pass through the intestinal cells. Once they leave the intestinal cells they are called **chylomicrons**. Chylomicrons do not enter directly into the bloodstream, but instead enter into the lymphatic system (see Figure 2.13). The lymphatic system then delivers the chylomicrons to the large veins of the neck via the thoracic duct. The fats then empty into the blood and are distributed throughout the body.

lipoproteins Substances that transport lipids in the lymph and blood. These substances consist of a central core of triglycerides surrounded by a shell composed of proteins, phospholipids, and cholesterol. Various types of lipoproteins exist in the body and differ based on size, composition, and density.

chylomicron A droplet made of resynthesized triglycerides wrapped in lipoproteins that is produced by the intestinal cells. Chylomicrons are passed from the intestinal cells where they then enter into the lymphatic system.

What happens to fats once they make it to the cells?

Fats have many functions within the body. However, bioenergetically, depending on the physical state of the body, the type of cell, and the need for energy, once fats reach the cells they can be either used for energy or stored for later use. For example, if energy demands are low and the bloodborne chylomicrons and their fatty payloads enter capillaries within adipose tissue or the liver, the chylomicrons can be acted upon by an enzyme located on the capillary wall called **lipoprotein lipase (LPL)**. LPL breaks the triglycerides inside the chylomicrons into free fatty acids and glycerol. The free fatty acids immediately diffuse into the fat or liver cells, where they are recombined with a new glycerol from inside the cells and once again re-formed into triglycerides. These newly formed triglycerides are stored until needed for energy. However, if the muscles are active and need energy, free fatty acids and chylomicrons in blood flowing through the capillaries of muscles can be used for

lipoprotein lipase (LPL) A specialized enzyme that breaks down triglycerides into glycerol and free fatty acids.

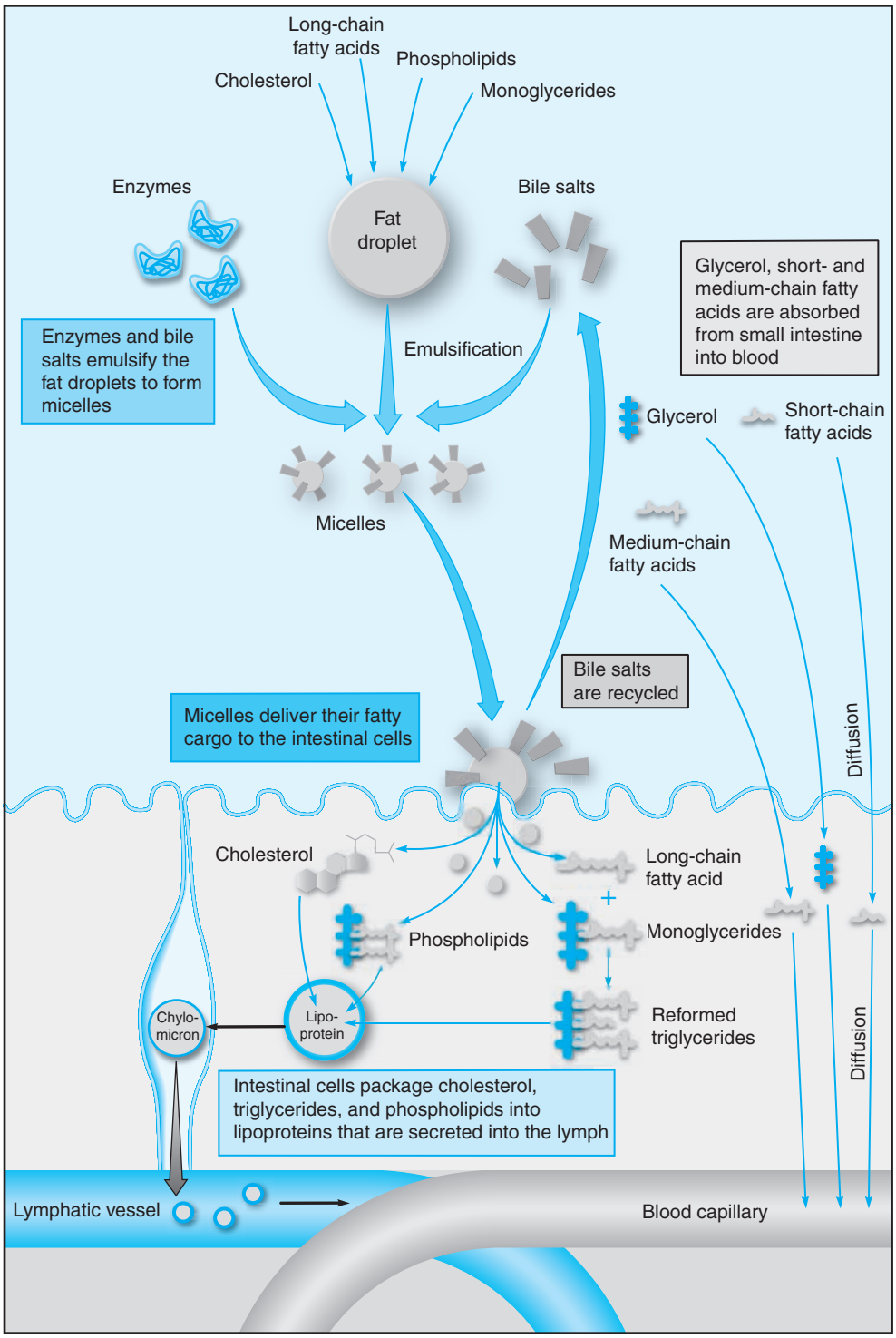


Figure 2.13 Summary of lipid absorption.

energy. LPL in the capillaries of muscles acts upon the triglycerides in the chylomicrons, similar to the LPL in adipose tissues. The free fatty acids in the blood, in addition to those released from the chylomicrons, are transported across the muscle cell membrane and into the interior of the cell where they are used for energy.

How are proteins digested, absorbed, transported, and assimilated in the body?

Of the three macronutrients, proteins are the least used by the body as a source of chemical energy; however, they play the biggest role in providing

structure to the body. Proteins also form the enzymes critical to the thousands of chemical reactions required to sustain life.

Proteins are made up of basic building blocks called amino acids. The proteins important to the human body are composed of 20 different amino acids. To make the proteins required, dietary proteins must supply the necessary amino acids. The following sections discuss how dietary proteins are digested and utilized by the body.

What happens to proteins once they are put into the mouth?

Once again, mastication initiates the digestive process; however, unlike carbohydrates and fats, which are subjected to digestive enzymes present in the saliva, proteins do not undergo enzymatic digestion in the mouth. The majority of protein digestion occurs in the stomach and upper portion of the small intestine. Hydrochloric acid (HCl) secreted by the stomach lining denatures proteins. **Denaturation** is the process by which the three-dimensional shape of the protein begins to unravel (see Figure 2.14). This makes the chemical bonds between the amino acids more accessible to digestive enzymes. The acidic environment, along with the churning of the food contents via the muscular contraction of the stomach, allows for greater mixing with the HCl, thereby allowing for a more thorough denaturation of the proteins.

denaturation A process by which proteins lose their three-dimensional shape and as a consequence their enzymatic activity.

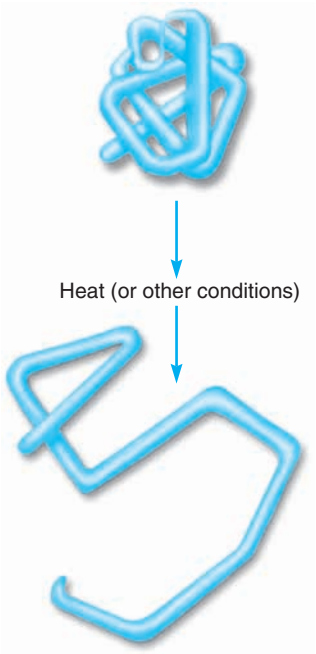


Figure 2.14 Denaturation. Exposing a protein to heat, acids, oxidation, and mechanical agitation can destabilize it, causing it to unfold and lose its functional shape.

In addition to the HCl, the enzyme pepsin begins breaking the proteins made up of longer chains of amino acids into shorter amino acid chains. The enzyme pepsin in the stomach is responsible for approximately 10–20% of protein digestion.[2] However, at this stage in the digestive process proteins are mostly broken down into smaller protein chains rather than single amino acids.

proteases A class of protein-digesting enzymes that break the chemical bonds holding amino acids together.

peptidases A group of protein-digesting enzymes that are released from cells of the small intestine. Peptidases work on breaking the chemical bonds of short-chain proteins (i.e., three or fewer amino acids), thereby yielding single amino acids.

The majority of digestion of protein takes place in the small intestine, where additional protein-digestive enzymes called **proteases** break down the protein chains into even smaller units. Both the pancreas and small intestine make and release proteases. Cells lining the small intestine also secrete **peptidases**, which continue to break the short protein chains into lengths of three or fewer amino acids. The resulting single amino acids and protein chains of two or three amino acids are absorbed by either facilitated diffusion or active transport. Most of the absorption takes place in the cells that line the duodenum and jejunum.

The final stage of protein digestion occurs inside the intestinal cells after absorption. Once inside the intestinal cells, other peptidases break the remaining chemical bonds in the protein chains to produce individual amino acids. Some of the absorbed amino acids are used by the intestinal cells themselves. The majority of amino acids are transported out of the intestinal cells via facilitated diffusion and enter into the portal system of blood vessels that go directly to the liver. Amino acids are then either used by the liver or released into the general circulation. Figure 2.15 provides a graphic summary of protein digestion.

Digestion and absorption of protein are quite efficient in the stomach and small intestine, and, as a result, very little protein makes it to the large intestine. Protein that does end up in the large intestine is excreted in the feces. Some medical conditions may cause protein digestion and absorption problems, and it is important for the sports nutrition professional to be aware of these conditions in order to adapt the dietary plan, particularly when dealing with athletes. For example, celiac disease is a digestive disorder that involves the inability to

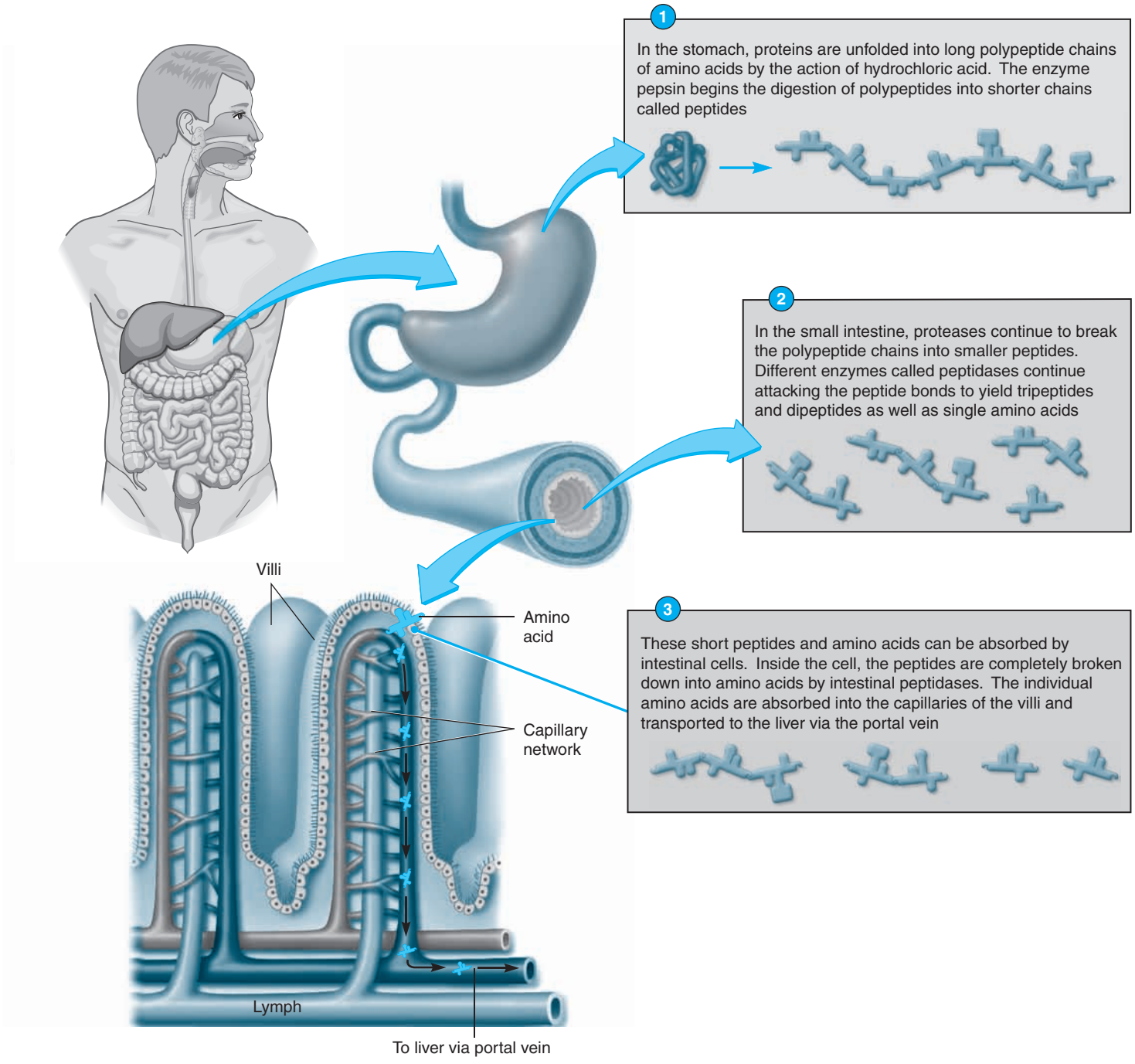


Figure 2.15 The breakdown of protein in the body. Digestion breaks down protein into amino acids that can be absorbed.

digest certain plant proteins. Athletes with celiac disease are not able to digest the protein in wheat, rye, oats, and other grains. Because these grains are excellent sources of carbohydrates that athletes need for energy, the sports nutrition professional must work closely with the athlete to find alternative plant protein/energy sources that will not exacerbate the symptoms and/or progression of the disease.

How are proteins absorbed into the intestinal wall?

Amino acid absorption occurs through facilitated diffusion and active transport (see Figures 2.8b and 2.8c). The majority of amino acids require active transport to gain access into the intestinal cells. The active transport process for amino acids is the same as described for glucose earlier in the chapter, although amino acids and glucose use different transport proteins. Similar amino acids share

the same active transport systems and carrier proteins. For example, the branched chain amino acids—leucine, isoleucine, and valine—all depend on the same carrier protein for absorption. Proteins consumed in the daily diet usually contain a variety of amino acids needed by the body. Because a variety of amino acids are being moved into cells through a variety of different carrier proteins, competition for the same membrane transporter is minimized, and the amino acids tend to be taken into the cell in proportions representative of the food's composition.

Taking supplements containing large amounts of a single amino acid can affect the absorption of other amino acids if they share the same transport carrier. For example, athletes trying to increase muscle mass may take supplements containing high doses of a specific amino acid or combination of amino acids. This may actually work against them because it could create competition for transport carriers that would result in the overabsorption of one amino acid at the expense of another.

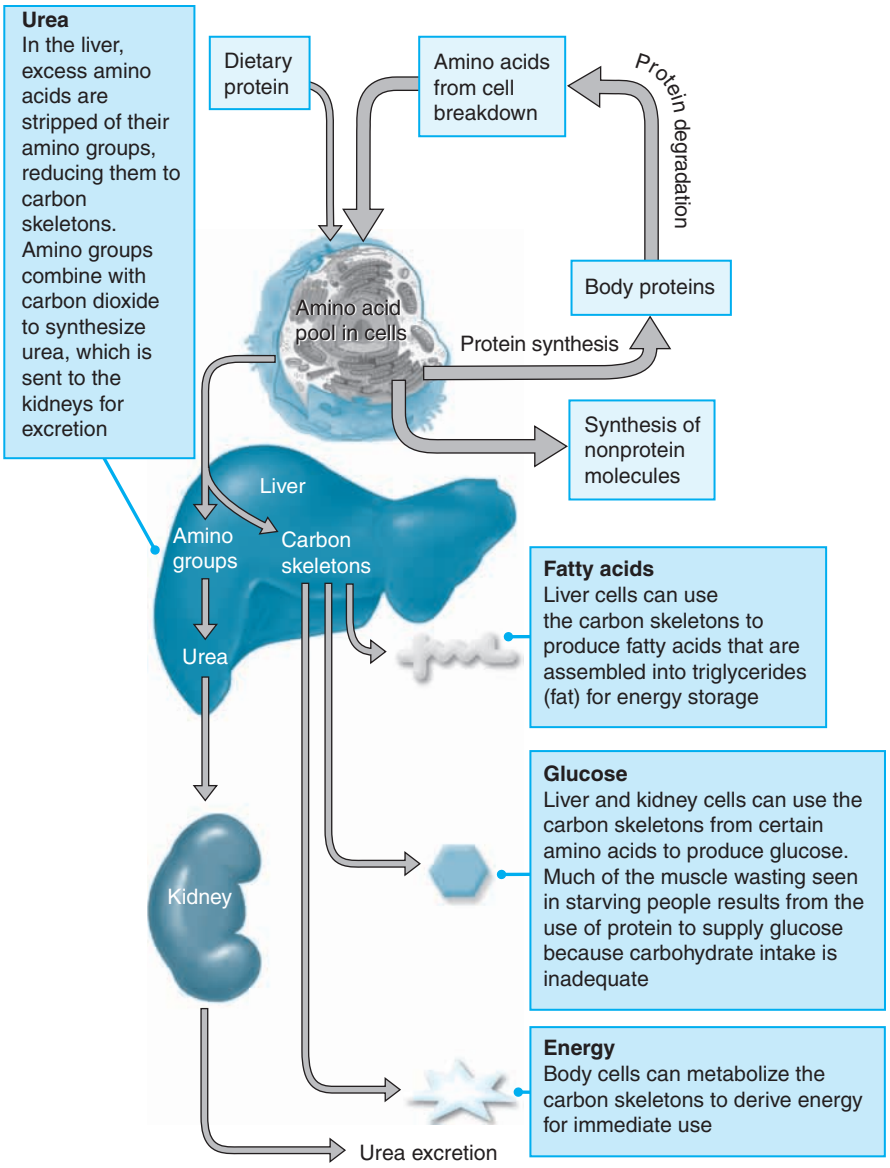


Figure 2.16 Amino acid pool turnover. Cells draw upon their amino acid pools to synthesize new proteins. These small pools turn over quickly and must be replenished by amino acids from dietary protein and degradation of body protein. Dietary protein supplies about one-third, and the breakdown of body protein supplies about two-thirds of the roughly 300 grams of body protein synthesized daily. When dietary protein is inadequate, increased degradation of body protein replenishes the amino acid pool. This can lead to the breakdown of essential body tissue.

What happens to amino acids once they make it to the bloodstream?

The amino acids that enter the bloodstream after digestion of ingested proteins become part of the body's **amino acid pool**, which consists not only of bloodborne amino acids, but also the amino acids found in other tissues, primarily skeletal muscle and the liver (see Figure 2.16). The blood and its circulating amino acids make up the central part of the body's amino acid pool. Amino acid concentrations in the blood are in equilibrium with the amino acids in the other compartments making up the amino acid pool. However, relatively few amino acids are circulating in the blood compared to the quantity found in muscle and the liver. If amino acid levels fall in one compartment, amino acids from the other compartments are mobilized to correct the imbalance. This sharing of amino acids between compartments can help ensure that needed amino acids are available when deficits arise.

Amino acids in the pool can be used for a variety of functions depending on the

amino acid pool The collection of amino acids found in body fluids and tissues that is available for protein synthesis.

gaining the performance edge

Maintaining adequate protein intake for athletes is essential for the continual replenishment of the amino acid pool.

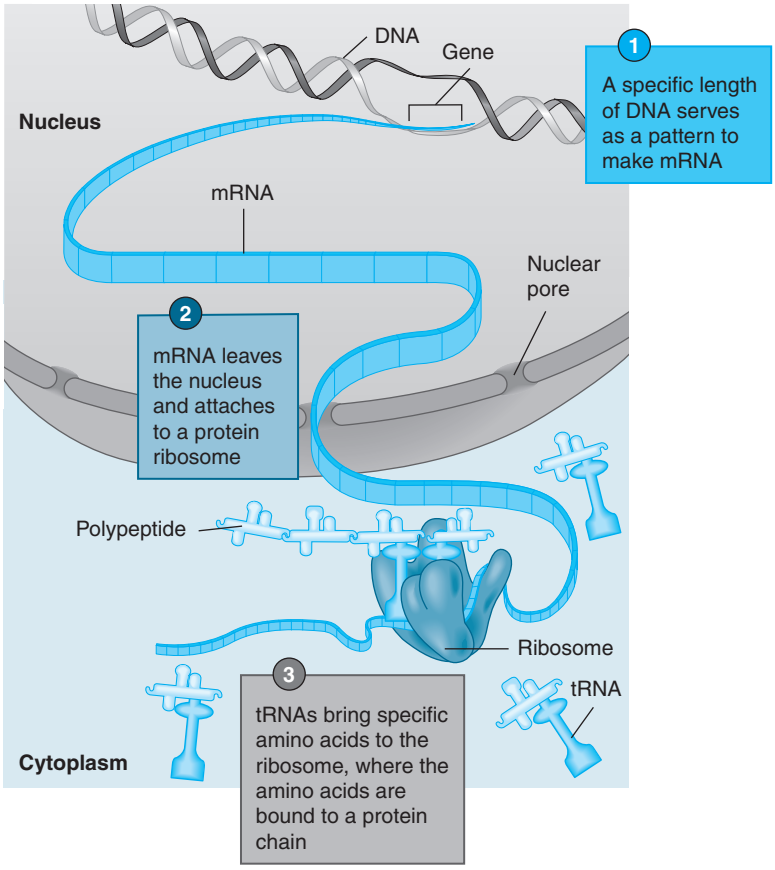


Figure 2.17 Protein synthesis. Ribosomes are our protein-synthesis factories. First mRNA carries manufacturing instructions from DNA in the cell nucleus to the ribosomes. Then tRNA collects and delivers amino acids in the correct sequence.

body's needs. They are primarily used to synthesize new structural proteins, enzymes, hormones, or other nitrogen-containing compounds. They can be metabolized for energy, particularly when carbohydrate stores of energy are low and demands for energy are high. Alternatively, when amino acid levels are in excess they can be converted to fat and stored for later energy use by the body (see Figure 2.16).

The sharing of amino acids between compartments is dynamic and ongoing. Proteins in the body are constantly turning over, requiring amino acids from the pool on a continual basis. However, this sharing of amino acids between compartments is a short-term fix for providing necessary amino acids. Daily dietary protein intake is essential to maintaining the body's amino acid pool. If protein intake is not adequate, proteins from muscle and other tissues will be cannibalized to provide the necessary amino acids, negatively affecting an athlete's training abilities and competitive performance.

What happens to amino acids once they make it to the cells of the body?

The amino acids circulating in the blood enter the cells of the body by facilitated diffusion. Once inside the cells, the amino acids become the building blocks for specific proteins. The specific protein constructed inside the cell is determined by current needs and/or the influences of outside factors such as hormones. For example, the hormone testosterone causes muscle cells to increase production of contractile proteins, thus causing the muscle to become bigger and stronger.

The actual instructions for making the specific proteins needed by the cell lie in the strands of **DNA (deoxyribonucleic acid)** found in the nucleus (see Figure 2.17). Segments of DNA that call for specific proteins are called **genes**. When a cell needs a particular protein, the specific gene with the instructions for that protein is copied in a process known as **transcription**. Transcription results in the formation of **messenger ribonucleic acid (mRNA)**, which is a genetic set of instructions on how to make the protein. Upon leaving the cell nucleus, messenger RNA delivers the instructions to the **ribosomes**, which are the cellular organelles located in the cell cytoplasm that build the protein. In a process known as **translation**, the ribosomes read the mRNA segment and begin attaching amino acids together in the sequence called for by the instructions. The amino acids needed by the ribosomes are delivered to the "protein construction site" by **transfer ribonucleic acid (tRNA)**. This process of tRNA delivering the needed amino acids to the ribosomes continues until the protein has been constructed.

deoxyribonucleic acid (DNA) The molecular compound that makes up the genetic material found within the nuclei of cells.

gene A specific sequence of DNA found within cell nuclei that contains information on how to make enzymes or other proteins.

transcription The process of copying genetic information from a specific DNA sequence through the formation of messenger RNA.

messenger ribonucleic acid (mRNA) A type of nucleic acid that carries the genetic instructions for protein synthesis from the cell nucleus to the ribosomes located in the cell cytoplasm.

ribosomes Cellular organelles that are responsible for protein synthesis.

translation The process in which proteins are produced by ribosomes as they read the genetic instructions found on messenger RNA.

transfer ribonucleic acid (tRNA) A type of ribonucleic acid that is responsible for delivering specific amino acids to the ribosome during production of protein.

gaining the performance edge

An athlete's diet must include high-quality complete protein sources or complementary protein foods so that the diet provides all of the essential amino acids. Failure to do so will result in inadequate protein synthesis, ultimately affecting training, recovery, and sport performance.

If an amino acid is required but not present at the time of protein construction, the protein-building process is stopped. If the required amino acid is a nonessential amino acid, the cell makes the amino acid and tRNA delivers it, continuing the building process. However, if the amino acid needed is an essential amino acid, the building process cannot continue, and the protein requested is not completed. This is why an athletic diet should include high-quality complete or complementary proteins so that all of the essential amino acids are available when needed. One missing essential amino acid can stop the construction of a protein. When this happens, the partially constructed protein is degraded, and its amino acids are used elsewhere or metabolized for energy.

How are minerals, vitamins, and water absorbed and transported in the body?

Minerals, vitamins, and water (unlike carbohydrates, proteins, and fats) do not need to be broken down into smaller units via digestion to be absorbed into the body. As foodstuffs are being digested, the vitamins and minerals within the foods are released into the intestinal contents. The majority of minerals released during digestion are absorbed in the duodenum and jejunum of the small intestine. The exceptions are sodium, potassium, and chloride, which are absorbed in the large intestine.

Vitamins are categorized as being either water soluble or fat soluble. The water-soluble vitamins (i.e., B-complex vitamins and vitamin C) dissolve in the watery mix of food in the GI tract and are absorbed along with the water. The majority of water and all of the water-soluble vitamins (see Figure 2.7) are absorbed in the small intestine. The water-soluble vitamins easily gain access to the blood and move freely throughout the body within the fluids both inside and outside of cells.

The fat-soluble vitamins (i.e., vitamins A, D, E, and K), when released from the digesting foods, dissolve in the fatty portions of the GI contents. As a result, they are transported along with the digested fats in micelles to the intestinal wall where they are absorbed via passive diffusion. Similar to the water-soluble vitamins, the majority of fat-soluble vitamins are absorbed in the small intestine (see Figure 2.7). A small amount of vitamin K is produced by bacteria in the large intestine and is then also absorbed. Once inside the intestinal cells the fat-soluble vitamins are packaged into the chylomicrons and then, along with other fats, transported via the lymph into the bloodstream. From there they are delivered throughout the body. Some are delivered and used by cells; others are stored along with fat in adipocytes. The fact that fat-soluble vitamins are stored in the body is one reason why taking high dosages of fat-soluble vitamins is not recommended.

Food for Thought 2.1

Digestion

This exercise tests your comprehension of the digestive process.

What is energy metabolism, and why is it important?

Energy metabolism is a foundational component of sports nutrition. Knowledge of the cellular machinery and metabolic pathways responsible for deriving energy from the macronutrients once they reach the cells is critical to the sports nutrition professional. Without knowledge of the three energy systems and how they work together to supply energy during specific activities, the sports nutrition professional is severely disadvantaged in regard to creating an individualized dietary plan. Knowledge of energy metabolism also enables the sports nutrition professional to objectively assess the potential effectiveness of dietary supplementation. Finally, comprehending energy metabolism enables sports nutrition professionals to educate their athletes about the energy needs of their sport, thus helping to dispel many of the misconceptions that abound in sports nutrition. The remainder of this chapter will define energy, identify which nutrients supply energy, and discuss how cells derive energy during rest and exercise.

What is energy?

Energy is an entity that is better explained or defined than shown because it has no shape, no describable features, and no physical mass. Energy is what enables cells, muscles, and other tissues of the body to perform work, or, in layperson's terms, to get things done. The cellular and bodily functions that keep humans alive require energy. Similar to an automobile that relies on the chemical energy of gasoline to run the motor, the cells of the body require chemical energy derived from the foods we eat to power their many different functions. In the case of sport performance, the muscle cells must derive

metabolism The sum total of all the energy required to power cellular processes and activities.

anabolic process A metabolic function that involves the building of more complex structures or chemical molecules and is associated with the storage of energy.

catabolic process A metabolic function that involves the breakdown of structures or molecules and is associated with energy being released.

basal metabolic rate (BMR) The minimum amount of energy required to sustain life at the waking state. BMR is usually measured in the laboratory under very rigorous conditions.

resting metabolic rate (RMR) The minimum amount of energy required to meet the energy demands of the body while at rest. RMR is typically measured instead of BMR because it is only slightly higher than BMR and is determined under less rigorous conditions.

kilocalories (kcals) The unit of measure for energy. It is the amount of heat energy required to raise the temperature of 1 liter of water 1 degree centigrade.

enough energy from nutrients to fuel muscle contraction. In short, an understanding of energy, where it comes from, and how the body uses and stores it is tantamount to understanding metabolism.

Metabolism is the sum total of the energy required by the body to perform all of its functions and thus is made up of both anabolic and catabolic processes (Figure 2.18). Anabolic processes involve the building of more complex structures or chemical molecules and require energy to occur; for example, when cells of the body use amino acids to make highly complex proteins or use simple sugars to make glycogen for storage within the cells (see lower half of Figure 2.18). Conversely, catabolic processes involve the breakdown of structures or molecules and are associated with energy being released; for example, when proteins, carbohydrates, and fats making up the foods we eat are broken down and used to provide energy. The absolute minimal amount of energy required to keep humans alive is called basal metabolic rate (BMR). A slightly higher amount of energy is required for resting metabolic rate (RMR). BMR and RMR are expressed in kilocalories (kcals), which are the commonly used units of measurement for energy. A kilocalorie is the amount of heat energy required to raise the temperature of 1 liter of water 1 degree centigrade, specifically from 14.5° C to 15.5° C. BMR and RMR measurements are obtained in different ways. BMR is measured under very stringent conditions and requires subjects to spend the night in a sleep lab. The subjects must be well rested, thermally neutral (i.e., neither hot nor cold), and in a transitional state of waking (i.e., not asleep but not fully alert) at the time of the actual BMR measurement. RMR measures are much easier to obtain. Subjects must fast for 12 hours but can drive to the laboratory, where they relax for 20 to 30 minutes in a supine/reclined position before their RMR is measured. BMR and RMR are used by sports nutrition professionals to determine an athlete's 24-hour energy expenditure. This total daily energy expenditure can be used both to establish the dietary caloric intake necessary to achieve energy balance and when counselling athletes in weight management.

Energy exists in six basic forms: chemical, nuclear, electrical, mechanical, thermal, and radiant.

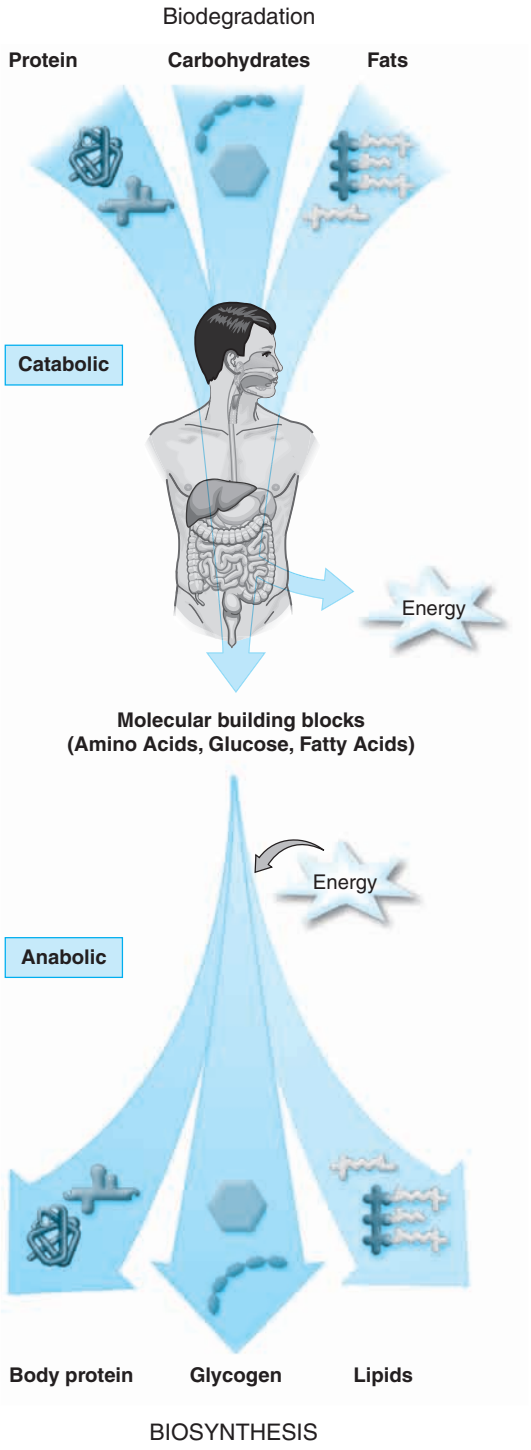


Figure 2.18 Metabolism. Catabolic processes result in biodegradation and energy release, and anabolic processes utilize energy to drive biosynthesis. Metabolism consists of both catabolic and anabolic processes.

gaining the performance edge

Macronutrients are needed in large quantities compared to other nutrients and act as sources of chemical energy in the body and as building blocks for biosynthetic processes. The macronutrients are more specifically known as carbohydrates, fats, and proteins.

However, the form of energy that humans and animals directly rely upon for survival is chemical energy. Chemical energy is energy that is stored within bonds between atoms of molecules. When the bonds between these atoms are broken, energy is released and can be used to perform work. On earth, the primary source of chemical energy for animal life originates from plants. Specifically, the plants use radiant energy from the sun to build high-energy bonds between atoms of carbon, hydrogen, nitrogen, and oxygen. In doing so, plants form molecules of carbohydrates, proteins, and fats, which serve as energy nutrients for the plants themselves, any animals that eat plants, and on up the food chain. Because animals digest the consumed carbohydrates, fats, and proteins and can convert them into their own forms of each (see Figure 2.18), we can get energy nutrients, also known as macronutrients, from both plant and animal sources. When plant and animal foods are eaten, the digestive system breaks the nutrients into their constituent parts so that they can be absorbed and transported to the cells. The cells can then use the bloodborne nutrients as building blocks for biosynthesis, store them for later use, or metabolize them for energy production.

What is the human body's source of chemical energy?

Based on the previous section, it could be concluded that the chemical energy in carbohydrates, fats, and proteins is the direct source of energy for cellular function. However, this is not the case. The direct source of energy for all biological processes comes from a high-energy molecule known as adenosine triphosphate (ATP). In short, the chemical energy from macronutrients is used to make another high-energy chemical known as ATP. The energy stored in the chemical bonds of ATP is released when the bonds are broken and can be used by the cells to perform biological work, as shown in Figure 2.19.

chemical energy Energy that is released as the bonds holding chemicals together are broken. In the human body the foods ingested provide chemical energy to make ATP, which is the ultimate source of chemical energy in the body.

adenosine diphosphate (ADP) A chemical compound that contains two phosphate groups attached to an adenosine molecule. ADP, when phosphorylated, becomes ATP.

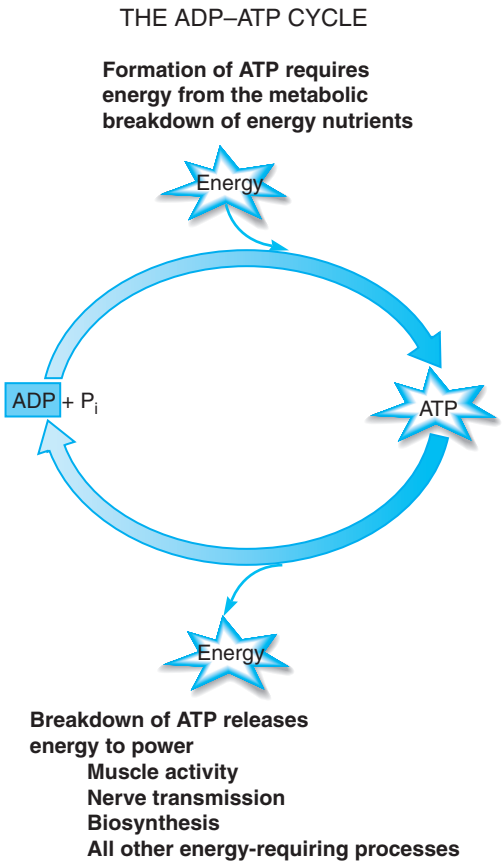


Figure 2.19 The ADP–ATP cycle. When extracting energy from nutrients, the formation of ATP from ADP + P_i captures energy. Breaking a phosphate bond in ATP to form ADP + P_i releases energy for biosynthesis and work.

ATP is an adenosine molecule with a chain of three phosphate groups attached to it in series (see Figure 2.20). The energy used by the body is stored in the molecular bonds between the second and third phosphate groups, as well as between the first and second groups. When the bonds between the second and third or first and second phosphate groups are broken, energy is released. Some of the released energy is used to perform work, and the remainder is lost as heat energy, which cannot be used by the body. When the bond to the third phosphate group is broken, the resultant products formed are an adenosine diphosphate (ADP) and an unattached inorganic phosphate group (P_i) (see Figure 2.20). ADP still has some energy potential for use by the body. If the last phosphate group is cleaved from the ADP, the

gaining the performance edge

ATP is the body's direct source of chemical energy for powering muscle contractions and other bodily functions.

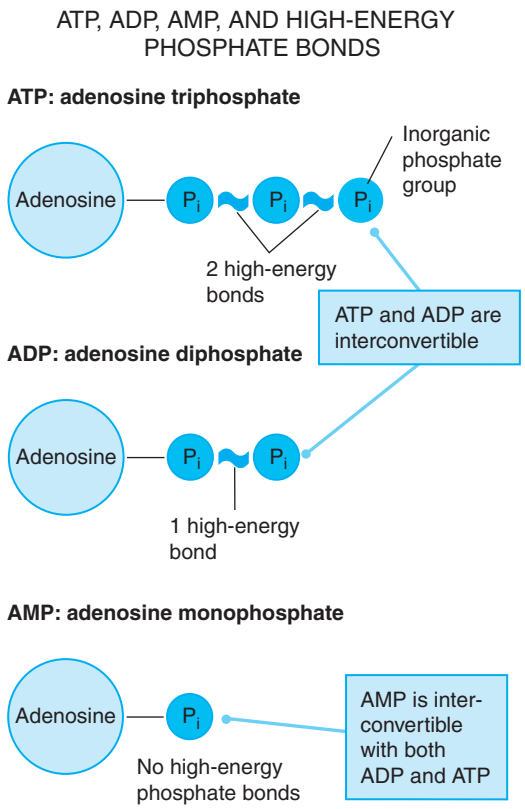


Figure 2.20 ATP, ADP, AMP, and high-energy phosphate bonds. Your body can readily use the energy in high-energy phosphate bonds. During metabolic reactions, phosphate bonds form or break to capture or release energy.

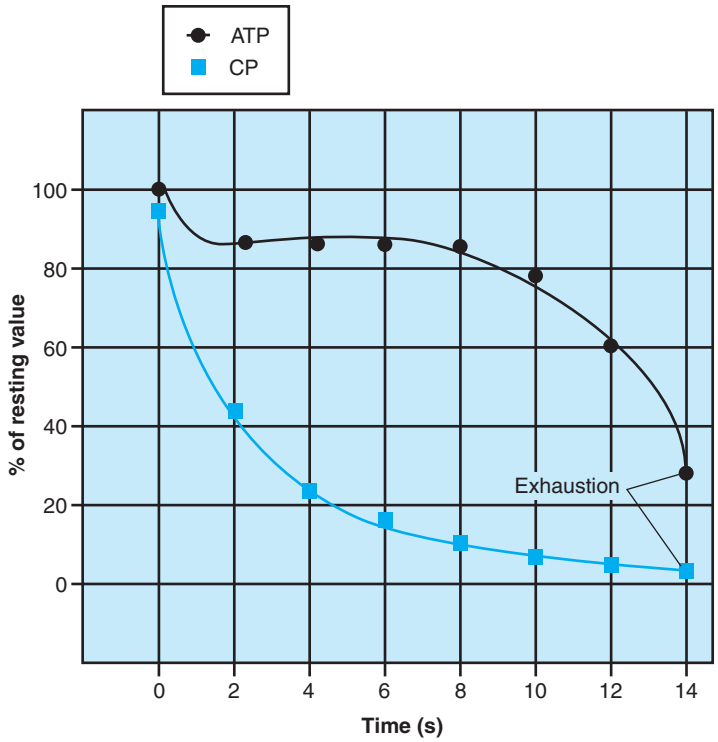


Figure 2.21 Effect of intense activity on ATP levels in muscle. Even when an activity results in exhaustion, ATP levels are not totally depleted.
Reproduced with permission from W. L. Kenney, J. H. Wilmore, and D. L. Costill, 2012, *Physiology of sport and exercise,* 5th ed. (Champaign, IL: Human Kinetics), 55.

result is the formation of **adenosine monophosphate (AMP)** and another P_i (see Figure 2.20).

Although ATP is the direct source of energy for cellular functioning, it is stored in very small quantities in the cells. For example, in muscle cells, ATP stores are so small they can be depleted in as little as 3 seconds of muscle activity. Despite the fact that ATP is stored in very limited amounts, it is important to note that cells never completely deplete their ATP stores. Figure 2.21 shows ATP levels during an intense sprint lasting 14 seconds. Note that at the point of exhaustion, roughly 30% of the muscle's ATP still remains. Obviously, athletes perform activities that last longer than 3 seconds every day, so the body must have ways of replenishing ATP once it is used. In fact, every cell, particularly muscle cells, can replenish any ATP that is used to keep the ATP fuel tank somewhat full. If ATP levels fall too low because the activity is so intense that the muscle cells cannot make ATP fast enough, protective mechanisms kick in that in turn cause **fatigue**. Fatigue is a noted decrease in performance level, which slows down or even stops the activity and thus protects the cell's ATP levels. Poor nutrition can directly affect ATP production and thus decrease sport performance. As a result, there must be a way for cells to make or replenish ATP once it has been used.

gaining the performance edge

Poor nutrition can directly affect ATP production and thus decrease sport performance.

How do cells make ATP?

To metabolize the energy nutrients, and in the process make ATP, the cells must possess the right metabolic equipment. Although there are many different types of cells that make up the body, they all have similarities. Figure 2.22 provides the names and functions of many of the parts of typical cells. For example, all cells have a **cell membrane** that encloses the contents of the cell, known as the **cytoplasm**. The

adenosine monophosphate (AMP) A chemical compound that contains a single phosphate group attached to an adenosine molecule.

fatigue A physical condition marked by the point in time at which the work output or performance cannot be maintained.

cell membrane The membrane that makes up the outer boundary of a cell and separates the internal contents of the cell from the external substances.

cytoplasm The interior of the cell. It includes the fluid and organelles that are enclosed within the cell membrane.

Organelles

Endoplasmic reticulum (ER)
- An extensive membrane system extending from the nuclear membrane.
- Rough ER: The outer membrane surface contains ribosomes, the site of protein synthesis.
- Smooth ER: Devoid of ribosomes, the site of lipid synthesis.

Golgi apparatus
- A system of stacked membrane-encased discs.
- The site of extensive modification, sorting, and packaging of compounds for transport.

Lysosome
- Vesicle containing enzymes that digest intracellular materials and recycle the components.

Mitochondrion
- Contains two highly specialized membranes, an outer membrane and a highly folded inner membrane. Membranes separated by narrow intermembrane space. Inner membrane encloses space called mitochondrial matrix.
- Often called the "powerhouse" of the cell. Site where most of the energy from carbohydrate, protein, and fat is captured in ATP (adenosine triphosphate).
- About 2,000 mitochondria in a cell.

Ribosome
- Site of protein synthesis.

Nucleus
- Contains genetic information in the base sequences of the DNA strands of the chromosomes.
- Site of RNA synthesis—RNA needed for protein synthesis.
- Enclosed in a double-layered membrane.

Cytoplasm
- Enclosed in the cell membrane and separated from the nucleus by the nuclear membrane.
- Filled with particles and organelles that are dipersed in a clear fluid called cytosol.

Cytosol
- The fluid inside the cell membrane.
- Site of glycolysis and fatty acid synthesis.

Cell membrane
- A double-layered sheet, made up of lipid and protein, that encases the cell.
- Controls the passage of substances in and out of the cell.
- Contains receptors for hormones and other regulatory compounds.

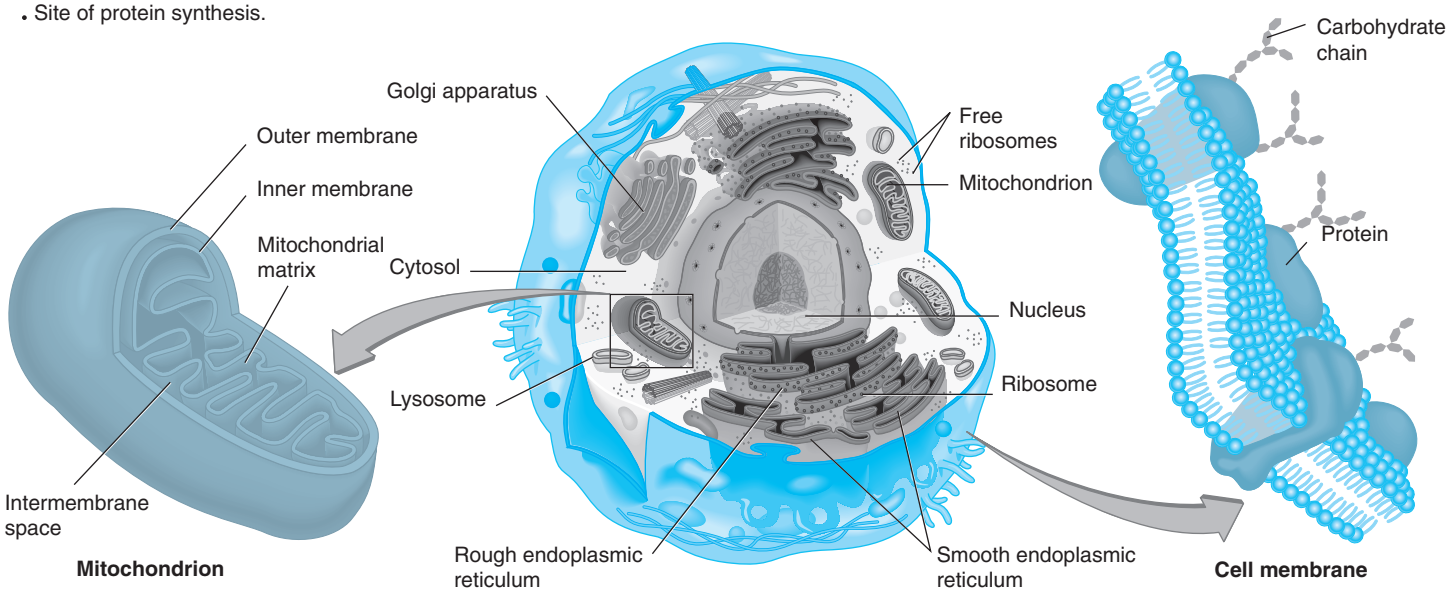


Figure 2.22 Component parts of a typical cell.

cell membrane serves as a barrier that regulates or prevents the influx of substances into or out of the cytoplasm. The watery component of the cytoplasm that fills much of the interior of the cell is known as the cytosol. Dissolved in the cytosol are enzymes, which are proteins responsible for accelerating each step in the metabolic pathways responsible for generating ATP. In addition, within the cytoplasm there are cellular structures known as organelles that perform specific functions. The organelle of most importance in regard to the production of ATP is the mitochondrion. The mitochondrion is sometimes

cytosol The watery or fluid part of the cytoplasm.

organelles Specialized structures found inside cells that perform specific functions. For example, the mitochondria are organelles responsible for the aerobic production of energy for the cell.

mitochondrion A specialized cellular organelle responsible for the aerobic production of ATP within the cell.

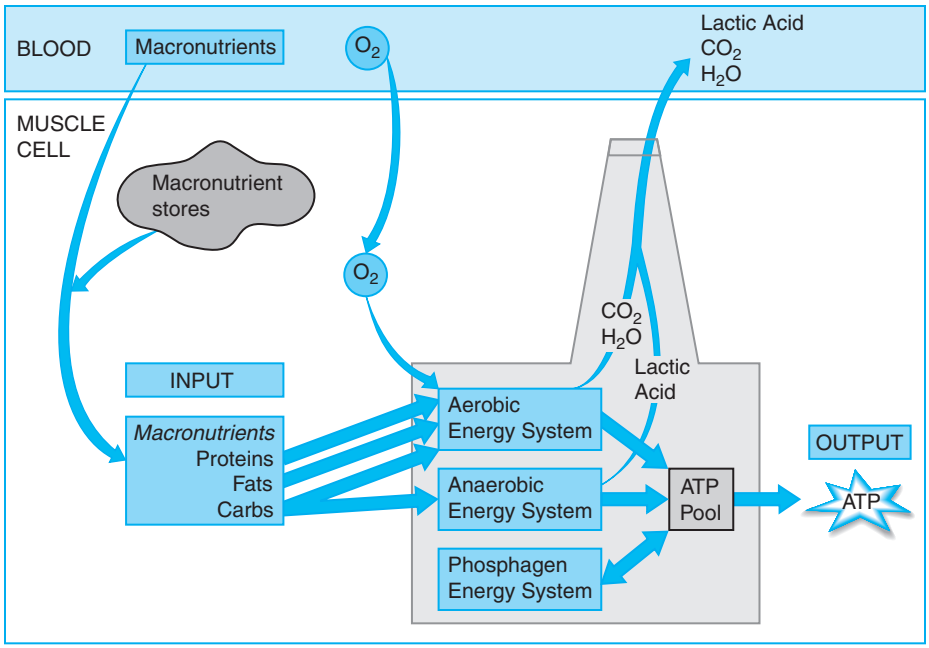


Figure 2.23 Metabolic factory analogy of energy metabolism.

more descriptively called the "aerobic powerhouse of the cell" because many of the metabolic pathways responsible for the aerobic production of ATP are found inside. Finally, each cell possesses a nucleus that contains the genetic information needed for making the enzymes and cellular structures required for ATP production.

To further explain ATP formation, a basic understanding of **bioenergetics** is necessary. Bioenergetics is the study of how energy is captured, transferred, and/or utilized within biological systems. Because this book deals with sports, the specific biologic system we will discuss in this chapter is muscle. To rebuild ATP, unattached phosphates must be reattached to AMP or ADP to re-form ATP. The process of resynthesizing ATP requires energy in and of itself, and this is where the energy trapped in the bonds of foods (i.e., macronutrients) comes into play. Using the analogy of a real-life factory, each of the muscle cells in the human body possesses what can be called a **metabolic factory**. These metabolic factories are responsible for manufacturing the cells' ultimate energy source, ATP (see Figure 2.23).

Continuing with the metabolic factory analogy, inside the factory is an **ATP pool** (i.e., the cell's inventory of readily available energy). Whenever a cell needs quick energy, it does not need to wait for the metabolic factory to produce ATP because ATP is already there ready to be used. However, the inventory of ATP is very small and must be maintained above a certain critical level, because if the cell runs out of ATP it can no longer function and dies. Fortunately, cells have three different energy systems (see Figure 2.23), each capable of providing ATP and preventing depletion of the ATP pool. The following section discusses each energy system in greater detail.

bioenergetics The study of energy transfer within a biological system.

metabolic factory The cellular enzymes, organelles, and metabolic pathways responsible for the production of energy within the cells.

ATP pool The muscle cell's inventory of readily available ATP.

What are the three energy systems?

The three energy systems that function within the metabolic factories of muscle cells to prevent ATP depletion are the **phosphagen system**, the **anaerobic system**, and the **aerobic system** (see Figure 2.23). These three energy systems have different properties when it comes to how much (i.e., their capacity to make ATP) and how quickly (i.e., their rate of ATP production) they can produce ATP (see **Table 2.1**).

What are the characteristics of the phosphagen system?

The phosphagen system is the simplest of the three energy systems and consists of the ATP pool itself and several other high-energy phosphates already present inside the cells that can provide energy almost as quickly as ATP. The phosphagen system is also known as the **immediate energy system** because it is capable of providing energy instantaneously. For example, when athletes burst from the starting blocks in a race, there must be an immediate source of energy available to enable them to go

phosphagen system The energy system composed of the high-energy phosphates ATP and creatine phosphate. It is also known as the immediate energy system. Of the three energy systems, it is capable of producing ATP at the fastest rate.

anaerobic system (anaerobic glycolysis) The energy system that has the capability to generate ATP in the absence of oxygen. The anaerobic system results in the formation of ATP and lactic acid.

aerobic system The energy system that relies upon the presence of oxygen to make ATP. Of the three energy systems, it is the slowest at producing ATP but has an almost unending capacity to make ATP.

immediate energy system The energy system composed of the high-energy phosphates ATP and creatine phosphate; as a result it is also known as the phosphagen system. Of the three energy systems, it is capable of producing ATP at the fastest rate.

TABLE 2.1 Comparison of Characteristics of the Three Energy Systems

Energy System	Energy System Complexity	Maximal Rate of ATP Production	Capacity to Make ATP	Lag Time to Increased ATP Production
Phosphagen	Low; one-step process	Very fast	Very limited	None; instantaneous
Anaerobic	Moderate; 12-step process	Fast; runs a close second	Limited	Seconds
Aerobic	Very high; many processes and steps	Very slow; distant third	Unlimited	Minutes

from no movement to maximum speed in fractions of a second. If ATP was not readily available at the start of the race, then the athlete's muscles would have to wait for the anaerobic and aerobic metabolic pathways to start producing energy. Because these pathways are lengthy, there would be a lag period before the increased production of ATP would be available. The phosphagen system serves as an energy buffer that fills the immediate need for ATP until the other two energy systems with higher capacities for generating ATP can ramp up their production of ATP. The high-energy phosphates that make up the phosphagen energy system are the cell's stores of ATP (i.e., the ATP pool) and another high-energy molecule, called **creatine phosphate (CP)** or, alternatively, **phosphocreatine**.

CP is a high-energy phosphate that in a one-step metabolic reaction can give its phosphate group to ADP to rebuild another ATP (see Figure 2.24). This metabolic reaction is accelerated by the enzyme **creatine kinase**.[3] The ATP pool and the one-step creatine kinase reaction that comprise the phosphagen energy system give it the highest rate of production of ATP of the three energy systems and enable it to provide instantaneous energy to the cells. Its high rate of ATP production makes the phosphagen energy system most relied upon when energy is needed quickly during very fast, powerful muscle contractions (see Figure 2.25).

Although the phosphagen system can supply ATP at very high rates, it has a limited capacity to generate ATP. Specifically, the phosphagen system would only be able to provide energy for 5 to 15 seconds, depending on the intensity of the activity.[4] As a result, it needs assistance from the other energy systems.

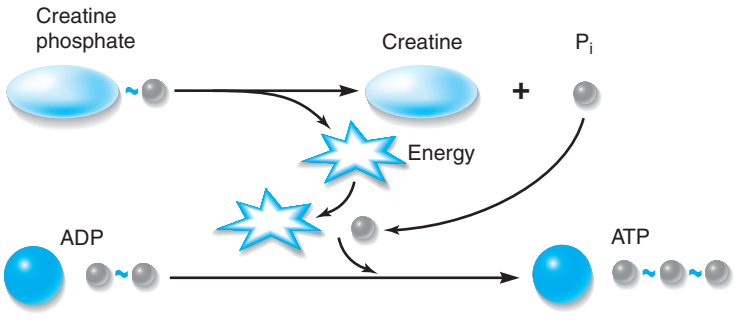


Figure 2.24 The ATP–CP energy system. To maintain relatively constant ATP levels during the first few seconds of a high-intensity activity, creatine phosphate releases energy and its phosphate (P_i) to regenerate ATP from ADP.

What are the characteristics of the anaerobic and aerobic energy systems?

As mentioned earlier, unlike the phosphagen system, which is basically an inventory of readily available high-energy phosphates within cells, the anaerobic and aerobic energy systems must generate ATP via more complex cellular processing (see Table 2.1). As a result, there is a slight lapse in time before the aerobic and anaerobic systems can ramp up and begin contributing ATP when an activity begins or changes in intensity. Compared to the phosphagen system, the anaerobic energy system is not quite as fast at producing ATP, but it has a slightly higher capacity to make more ATP. In contrast, the aerobic energy system has an unlimited capacity to make ATP and far exceeds the phosphagen and anaerobic systems in this characteristic. However, because it is a complex system, its rate of ATP production is much slower than the other two. In short, each energy system has different characteristics that help to satisfy our body's energy needs no matter what the activity.

creatine phosphate (CP) A high-energy phosphate stored inside muscle cells.

phosphocreatine A high-energy phosphate stored inside muscle cells. It is also known as creatine phosphate.

creatine kinase The enzyme that catalyzes the reaction transferring phosphate from creatine phosphate to adenosine diphosphate to make ATP.

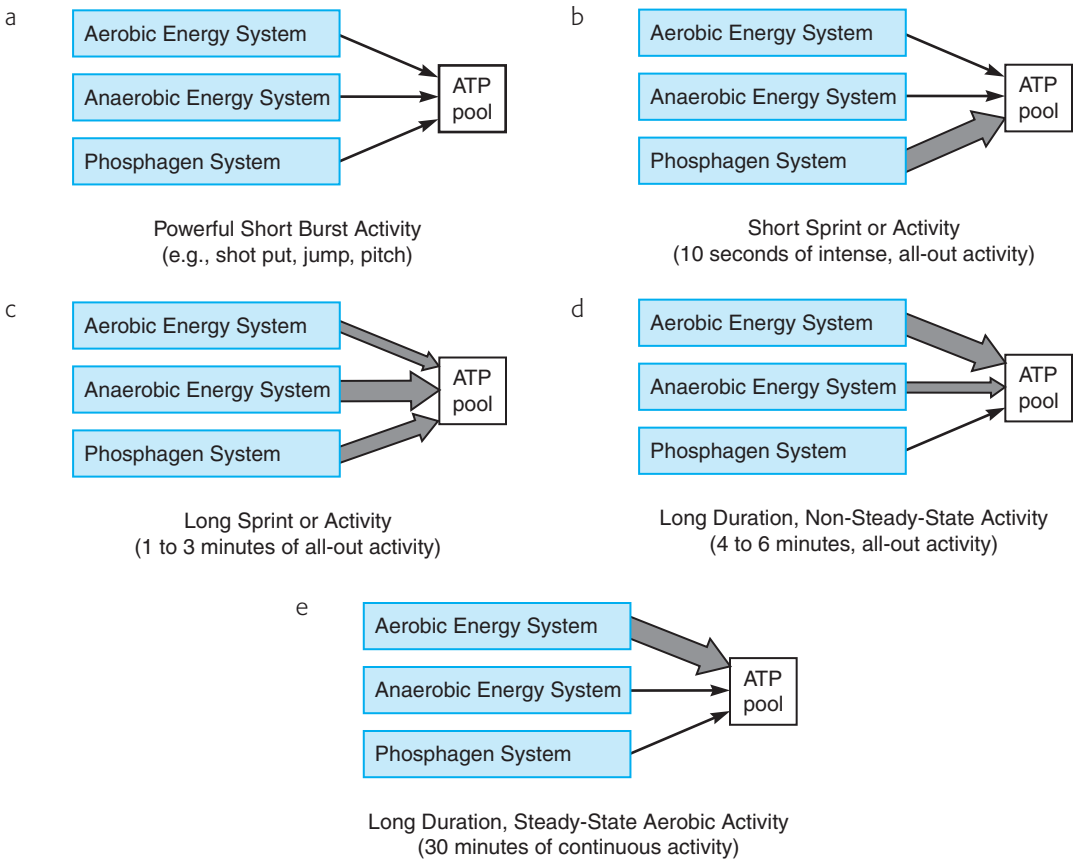


Figure 2.25 The three energy systems work together to meet the energy demands of any level of physical activity. Width of arrow denotes degree of energy contribution.

How do the energy systems work together to supply ATP during sport performance?

During sports, the energy requirement of muscle is related to the intensity and duration of the activity. In other words, slow movements do not require ATP to be supplied as rapidly as more powerful, fast movements do. As discussed earlier, the existing ATP pool in muscle cells is very small. Therefore, it is imperative that the three energy systems work together to maintain ATP levels. Remember, muscle cells never run out of ATP. Thus, if an activity is so intense and burns ATP so quickly that the three energy systems cannot supply ATP fast enough to prevent ATP depletion, fatigue ensues (Figure 2.21). Fatigue causes a decrease in the level of activity, resulting in a lower energy demand, thereby giving the energy systems a chance to begin replenishing the level of ATP.

To prevent fatigue and maintain ATP levels above the threshold for fatigue, the energy systems must work together, taking advantage of their unique characteristics to meet the metabolic demands for ATP. Of the three energy systems, the muscle cells rely predominantly on the aerobic system because of its unending ability to make ATP. If the energy requirements of an activity are low enough for the aerobic energy system to meet the energy demands, exercise can be continued for a long duration. This results in a condition called **steady state exercise**, where the energy demands are being met primarily by the aerobic system (see Figure 2.25e). The more highly trained the aerobic energy system, the faster a person can move while remaining in a steady state.

steady state exercise Any level or intensity of physical activity in which the energy demand for ATP is met by the aerobic production of ATP.

Endurance athletes train every day to challenge and improve the aerobic systems of their muscle cells. Their muscles respond to the daily demands by increasing the cellular organelles where aerobic production of ATP occurs: the mitochondria. As mentioned earlier, increasing the number and size of mitochondria enables the cell to greatly increase the speed with which it makes ATP. Because ATP can be supplied much more rapidly, the speed of the activity can be performed more quickly while the athlete remains in a steady state. This is why highly trained marathoners

can run 26.2 miles at speeds that untrained persons could not run for even 1 mile without fatiguing.

When the energy needs of the muscle cannot be met by the aerobic system, the other two systems are needed to supplement the deficiency in ATP. If the activity is just slightly above the ability of the aerobic system to supply ATP, then the amount supplemented by the other two systems is low, and the activity can be continued for quite a while before fatigue sets in (see Figure 2.25d). As the intensity of the activity increases, the ability to produce energy through the aerobic pathways decreases, and therefore the reliance on the other two systems increases, causing fatigue to ensue more quickly. For example, if a marathoner decided to increase her running speed to something faster than her normal race pace, the demand for ATP production would go up. If the increase in speed was slightly above the aerobic system's ability to supply ATP, then the phosphagen and anaerobic systems would have to help fill the slight energy deficit. However, the energetic demand placed on the phosphagen and anaerobic systems would be relatively low, and the runner could maintain this increased pace for approximately a mile or two before fatigue sets in. However, if the marathoner decided to sprint as fast as possible, then the all-out sprint would require ATP to be supplied at rates well above the aerobic system's ability to supply it. In this scenario the muscles would have to rely much more heavily on the other two energy systems, and exhaustion would set in much more quickly. If the marathoner timed the final sprint just right, sprint speed could be maintained for approximately 200 meters before the muscles' ATP stores fell to critically low levels. Recall that when ATP levels get low exhaustion sets in (see Figure 2.21). Sprinting places a huge demand on the phosphagen and anaerobic energy systems, and, as a result, regular sprint training causes muscles to adapt. The muscles increase their stores of ATP and CP. In addition, the muscle cells make more enzymes such as creatine kinase and others associated with anaerobic metabolism. The end result is a sprint athlete who can maintain his or her maximum running speed for fractions of a second longer than the competition and thus perhaps win the race. **Creatine monohydrate** is a dietary supplement that increases the levels of CP in the muscle, and thus is a popular item with sprint and power athletes.[5] Creatine monohydrate bolsters the immediate energy system's ability to supply ATP, thus delaying fatigue in high-intensity activities.[6,7]

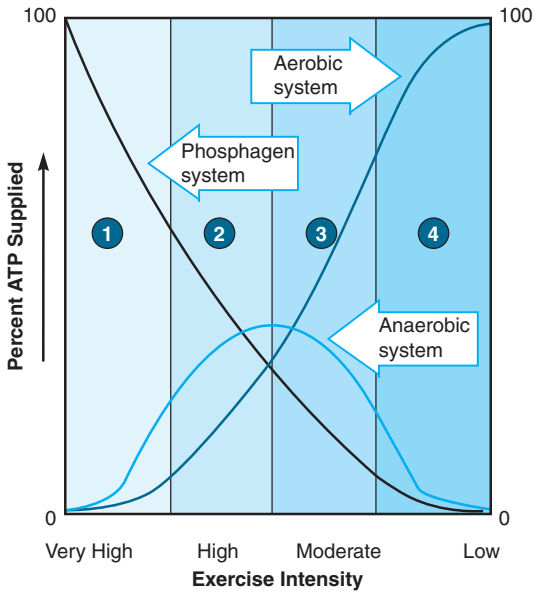


Figure 2.26 ATP contribution of the three energy systems to maximally sustained activities of very short, high-intensity exercise, such as the shot put (i.e., left margin of graph), to low-intensity maximally sustained exercise lasting longer than 3 minutes, such as running a marathon (i.e., right margin). Note: The longer the duration of "maximally sustained activity," the lower the exercise intensity. Area 1 spans from fractions of a second to 30 seconds, area 2 spans from 30 seconds to 1.5 minutes, area 3 spans from 1.5 minutes to 3 minutes, and area 4 is for time longer than 3 minutes.
Source: Reprinted with permission of the McGraw-Hill Companies from Bower RW, Fox EL. *Sport Physiology,* 3rd ed. Dubuque, IA: William C Brown Publishers; 1992.

Athletes with energy needs somewhere between those of the sprinter and those of the marathoner rely on the three energy systems working together. The reliance on each of the systems depends on the nature of the sport. In other words, there exists an **energy continuum** (see Figure 2.26). The energy required for various sports activities falls at different points along this energy continuum. For example, an athlete who runs the mile moves at speeds somewhere between those of the sprinter and those of the marathoner (see Figure 2.25d). The intensity of the miler's run is higher than that which can be provided by the aerobic system but not so intense that it puts a huge demand on the phosphagen system. In this case the anaerobic system plays a larger role in working with the aerobic system to provide the needed ATP. The bottom line is that any activity

creatine monohydrate A dietary supplement that can help improve an athlete's anaerobic strength and power by increasing levels of creatine phosphate in muscles.

energy continuum A continuum of activity levels spanning from lowest to maximum, with all points in between requiring slightly increasing rates of energy production.

TABLE 2.2 Metabolic Pathways Associated with the Three Energy Systems

	Phosphagen	Anaerobic	Aerobic
Metabolic pathways	None	Glycolysis	Beta-oxidation Glycolysis Deamination Citric acid cycle Electron transport chain

TABLE 2.3 Energy Nutrients and the Sequence of the Aerobic Metabolic Pathways That Metabolize Them for Energy

	Carbohydrates	Fats	Proteins
Glycolysis	1		
Beta-oxidation		1	
Deamination			1
Citric acid cycle	2	2	2
Electron transport chain	3	3	3

relies on the optimal blending of energy production by the three energy systems (see Figure 2.26).

What metabolic pathways are involved with the energy systems?

The phosphagen system does not involve any metabolic pathways because its function is based on already existing stores of high-energy phosphates. The cellular processing required to make ATP anaerobically or aerobically occurs via **metabolic pathways**. Metabolic pathways can be **anabolic pathways**, which require energy and result in the formation of more complex molecules, or **catabolic pathways**, which release energy and result in the breakdown of molecules (see Figure 2.27). The anaerobic and aerobic metabolic pathways are catabolic. In short, anaerobic and aerobic metabolic pathways are sequential steps in which foods (i.e., carbohydrates, fats, and proteins) are broken down (see **Tables 2.2** and **2.3**). In other words, these metabolic pathways are assembly lines in reverse (i.e., disassembly lines). Instead of building something in a stepwise systematic fashion, metabolic pathways slowly break apart food molecules in an organized stepwise order. This helps the cells to capture as much energy as possible from foods to make ATP. Although there is some commonality in the metabolic pathways required to break down carbohydrates, fats, and proteins, there are a couple pathways that are unique depending on the energy nutrient being processed and/or the availability of oxygen.

metabolic pathways Sequentially organized metabolic reactions that are catalyzed by enzymes and result in the formation or breakdown of chemicals within the body.

anabolic pathway A metabolic pathway that requires energy and results in the formation of more complex molecules.

catabolic pathway A metabolic pathway that degrades complex compounds into simpler ones and in the process gives off energy.

The anaerobic energy system (see Figure 2.28), involves one metabolic pathway, called anaerobic glycolysis. The only macronutrient that can be broken down via glycolysis is carbohydrates. **Glycolysis** is unique in that it can be part of both the anaerobic and aerobic energy systems. When adequate amounts of oxygen are not available and energy is needed, the end product of glycolysis (i.e., pyruvate) is converted to lactic acid (see Figure 2.28). This last step or reaction enables glycolysis to continue producing ATP without the need for oxygen, which is why it is called the anaerobic energy system. **Anaerobic** means without oxygen. Alternatively, if oxygen is present, then pyruvate is not converted to lactic acid. Instead, it is

glycolysis A metabolic pathway that is responsible for the breakdown of glucose. It is unique in that it can function with or without the presence of oxygen.

anaerobic A term used to describe a condition in which oxygen is not present.

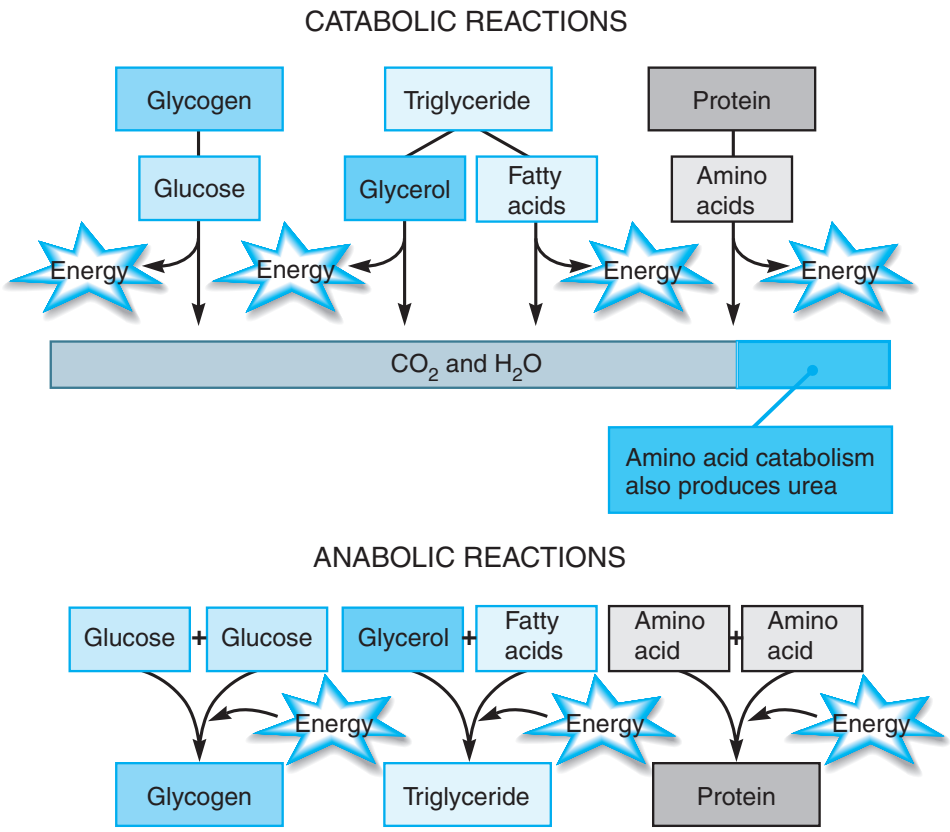


Figure 2.27 Catabolism and anabolism. Catabolic reactions break down molecules and release energy and other products. Anabolic reactions consume energy as they assemble complex molecules.

metabolized in other metabolic pathways that are associated with the aerobic energy systems discussed in the following section.

Unlike the phosphagen system, which at its longest is one step, the anaerobic system involves a metabolic pathway (i.e., glycolysis) of 12 steps. Because it is lengthier and more complex than the phosphagen system, it is a little slower to adapt to changes in activity level. However, it is much faster to adapt than the aerobic energy system, which is the slowest of the three systems. The anaerobic energy system is a major contributor to intense (i.e., maximal effort) activities that last from 1 to 3 minutes (see Figure 2.25c). During these activities, oxygen availability is limited because of the intense muscle contractions that close off blood vessels and limit delivery of oxygen, at least in large enough quantities to completely meet the energy demands of the activity.

Although the anaerobic system's rate of production of ATP is fairly high, its capacity for making ATP is limited (see Table 2.1). The resulting product of anaerobic glycolysis is lactic acid. When lactic acid is produced quickly it accumulates in the muscle, and when levels get high enough, fatigue ensues. To experience the fatigue caused by lactic acid build-up, one only needs to run around an outdoor track as fast as possible. The burning feeling experienced in the muscles is caused by lactic acid build-up.

Compared to the other energy systems, the aerobic system is the slowest at producing ATP, but it has an unlimited ability to make ATP. The aerobic system provides the fuel for resting metabolic needs. It also is the energy system most relied upon for longer duration, continuous activities that can be performed for minutes to hours. The aerobic energy system is also the longest and most complex of the three energy systems (see Table 2.1). It involves five different metabolic pathways (see Table 2.2). The metabolic pathways involved depend on the chemical structure of the food molecule being broken down (see Table 2.3 and Figure 2.29). The end products of the aerobic energy system are ATP, carbon dioxide, and water. It should be noted that carbon dioxide and water are the very same molecules used by plants to make carbohydrates, along with fats and proteins. In short, plants use carbon dioxide from the air, water from the soil, and light energy from the sun to make the energy nutrients. During aerobic metabolism our cells break the foods back down to their constituent parts of carbon dioxide and water, thus releasing the chemical energy in the foods (see Figure 2.28) and using it to make ATP. The carbon dioxide and water released from the body can then be reused by plants to make more energy nutrients, thus completing the ongoing energy cycle.

What pathways are associated with the aerobic breakdown of carbohydrates?

The first metabolic pathway carbohydrates must pass through is the glycolytic pathway (see Figure 2.28). When sufficient oxygen is present, **pyruvate**, which is the end product of

pyruvate The end product of glycolysis.

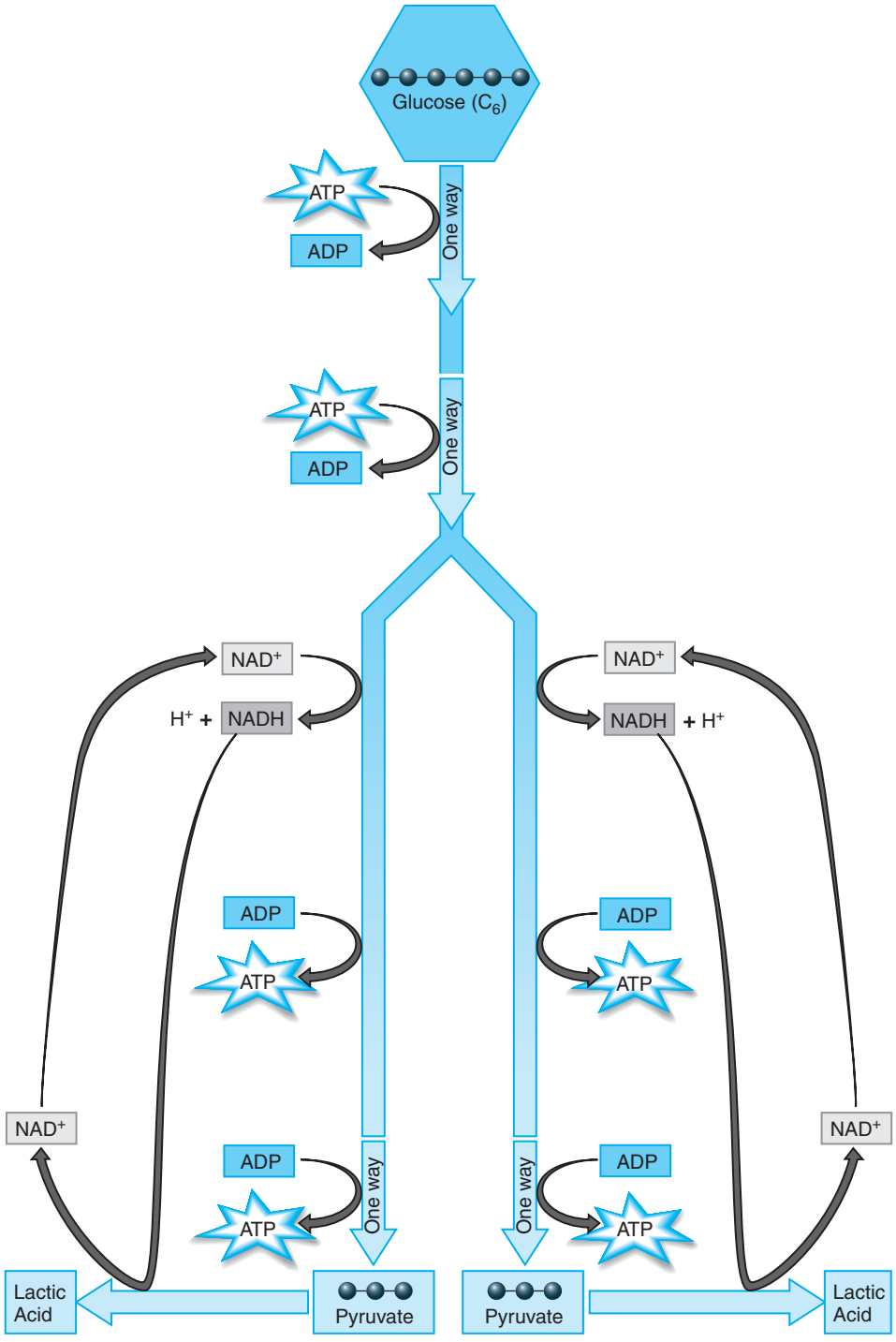


Figure 2.28 Anaerobic glycolysis.

glycolysis, is converted to acetyl coenzyme A (acetyl CoA) (see Figure 2.30) rather than converted to lactic acid as during anaerobic metabolism. The acetyl CoA then enters into the **citric acid cycle** (see Figure 2.31), which is a series of reactions that occur inside of the mitochondria of the cell. The primary purpose of the citric acid cycle is to strip hydrogens from the molecules as they pass through. The stripped hydrogens are picked up by special carrier molecules known as **nicotinamide adenine dinucleotide (NAD)** and

citric acid cycle One of the major metabolic pathways of the aerobic energy system. It is also known as the Krebs cycle or the tricarboxylic acid cycle. Its main role is to strip hydrogens from compounds passing through it.

nicotinamide adenine dinucleotide (NAD) One of two electron carriers that is responsible for shuttling hydrogens from one metabolic step or pathway to another.

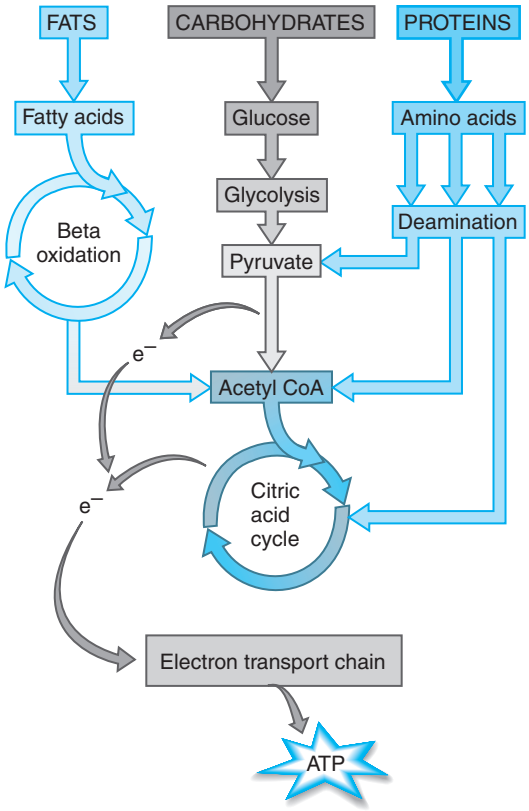


Figure 2.29 Aerobic metabolism of the macronutrients.

flavin adenine dinucleotide (FAD). NAD and FAD combine with the stripped hydrogens to form NADH and FADH, respectively. The attached hydrogens are transported to the final aerobic pathway, the **electron transport chain (ETC)** (see Figure 2.32).

flavin adenine dinucleotide (FAD) One of two electron carriers that is responsible for shuttling hydrogens from one metabolic step or pathway to another.

electron transport chain (ETC) The final metabolic pathway of the aerobic energy system. It is responsible for transferring hydrogens from one chemical to another and in the process making ATP and water.

The hydrogen transfer molecules associated with the electron transport chain are located on the inner membrane of the mitochondria. The transfer of hydrogens down the ETC begins once the hydrogen carriers NADH and FADH release their hydrogens to the ETC (see Figure 2.32). The resulting NAD and FAD are available to cycle back to the citric acid cycle to pick up more hydrogens. The hydrogens dumped into the ETC are transferred from one transfer molecule to another. In the process of hydrogen transfer, energy is given off and captured in the form of ATP. The final acceptor molecule for the hydrogens being passed down the ETC is oxygen, which results in the formation of water (see Figure 2.32). The ETC is the metabolic pathway that generates the most ATP during aerobic metabolism. The problem is that the ETC is the final pathway in aerobic metabolism, and as a result it takes time for ATP formation to increase in response to exercise or activity.

The citric acid cycle and the electron transport chain are aerobic pathways that are common to all three energy nutrients. As already noted, both of these metabolic pathways are found in the mitochondria of the cells. For this reason, mitochondria are called "aerobic powerhouses" of the cells. Endurance-type training challenges these metabolic pathways to produce energy more rapidly. The cells adapt

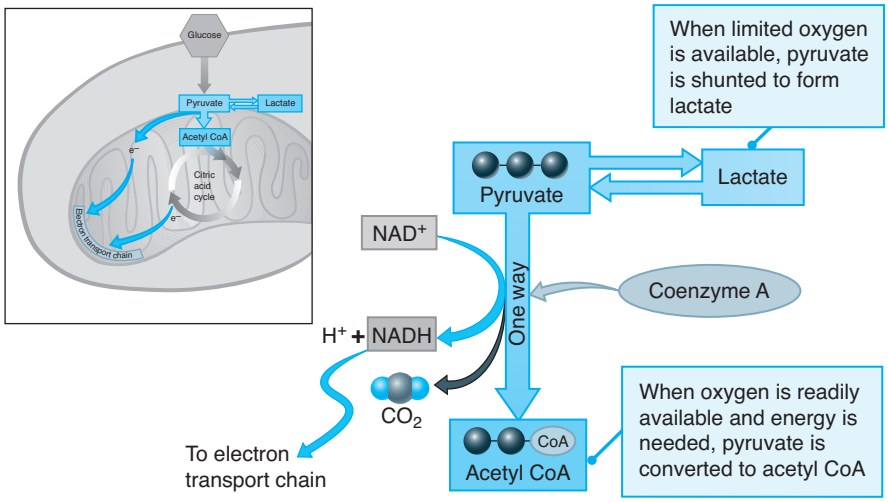
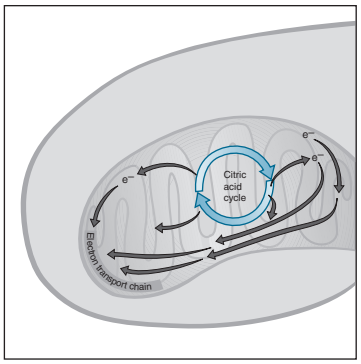


Figure 2.30 Pyruvate to acetyl CoA. When oxygen is readily available, each pyruvate formed from glucose yields one acetyl CoA and one NADH.



The citric acid cycle produces 3 NADH and 1 $FADH_2$ which carry pairs of high-energy electrons to the electron transport chain. It also forms one GTP which is readily converted to 1 ATP.

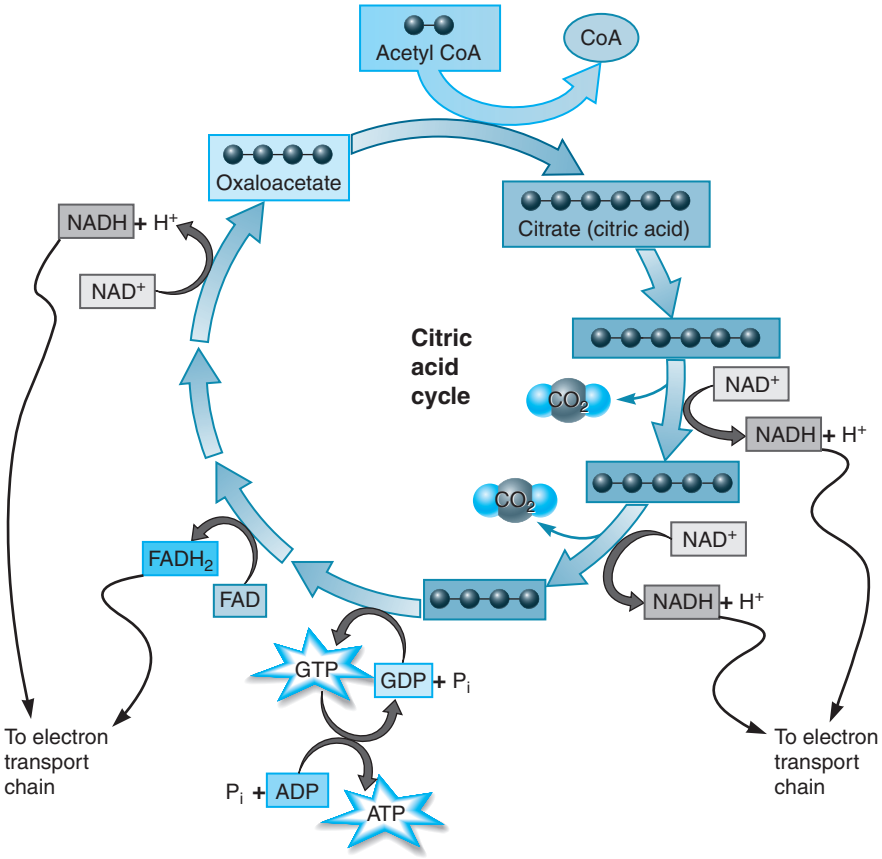


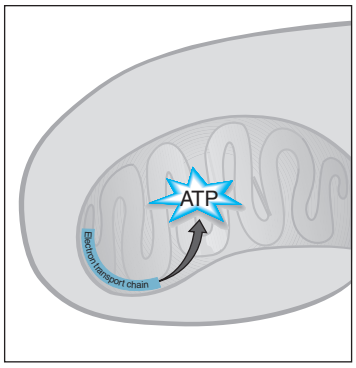
Figure 2.31 The citric acid cycle. This circular pathway conserves carbons as it accepts one acetyl CoA and yields two CO_2, three NADH, one $FADH_2$, and one guanosine triphosphate (GTP), a high-energy compound that can be readily converted to ATP.

to endurance training by increasing the size and number of mitochondria, allowing for greater production of ATP aerobically.[8] This is one of the reasons why endurance athletes can perform at higher intensities for a longer duration than untrained persons.

What pathways are associated with the aerobic breakdown of fats and proteins?

Fats and proteins cannot be metabolized via glycolysis and therefore must pass through other pathways before entering into the citric acid cycle and ETC (see Figure 2.29). Fats must first be metabolized via **beta-oxidation**, which is a cyclical pathway that is found within the confines of the mitochondria. Each pass of a fatty acid through beta-oxidation cleaves off two carbon fragments from the end of the fatty acids. Each pass also results in the formation of an NADH and an FADH. The two carbon fragments are converted to acetyl CoA, which then enters the citric acid cycle and ultimately

beta-oxidation The first metabolic pathway of fat metabolism, which cleaves off two carbon molecules each time a fatty acid chain cycles through it.



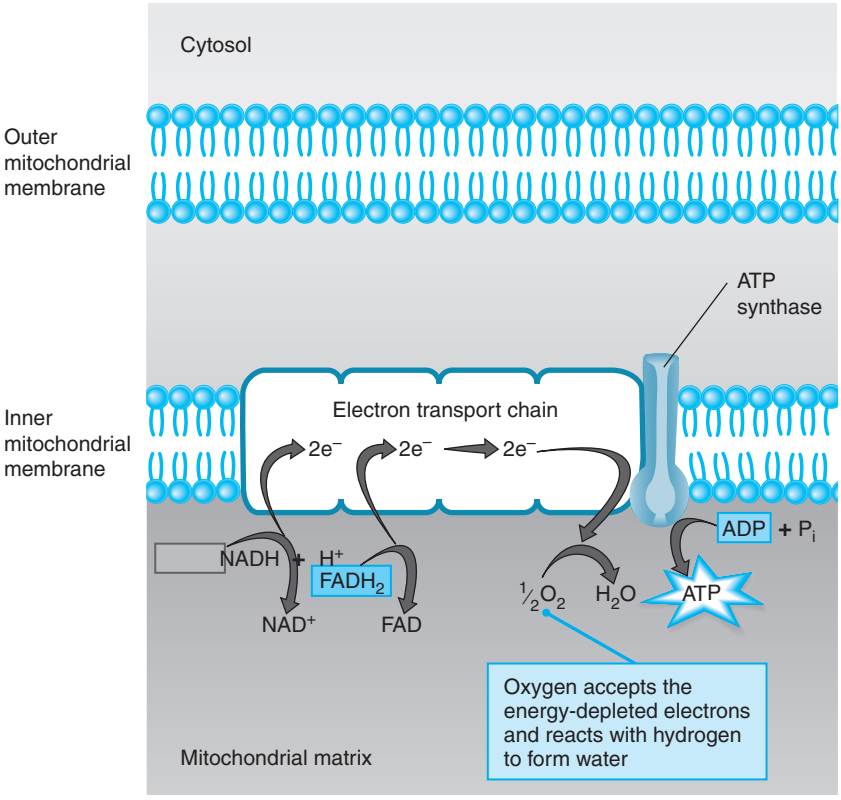


Figure 2.32 Electron transport chain. This pathway produces most of the ATP available from glucose, as well as fats and amino acids. Mitochondrial NADH delivers pairs of high-energy electrons to the beginning of the chain. Each of these NADH molecules ultimately produces 2.5 ATP. The pairs of high-energy electrons from FADH2 enter this pathway farther along, so one FADH2 produces 1.5 ATP.

the ETC. The NADH and FADH transfer their hydrogens to the ETC for use in ATP production.

Proteins contain nitrogen components in their molecular structure. These nitrogen-containing components cannot be used by the body and thus must first be cleaved from the protein before it can be metabolized for energy. The process in which the nitrogen group is cleaved from proteins is called **deamination** (see Figure 2.33). Once the nitrogen is removed, the remaining carbon molecule can pass through the citric acid cycle and then the ETC to produce ATP (see Figure 2.29). However, it should be noted that proteins are not normally a major source of energy (they provide less than 10% of energy for exercise) unless energy expenditure is high and/or carbohydrate intake is low.[9]

deamination The metabolic pathway that is responsible for removing the nitrogen or amine group from the carbon structure of amino acids.

gluconeogenesis The formation of glucose from noncarbohydrate sources such as proteins.

When diets are low in carbohydrates or when an athlete is involved in training that depletes carbohydrate stores, the body must get its carbohydrates from somewhere else. It does so by converting proteins in the body to carbohydrates in a process known as **gluconeogenesis** (see Figure 2.34). During gluconeogenesis, proteins are broken down into amino acids, transported to the liver, and converted to the carbohydrate glucose, which can then be used for energy by the body tissues. Unfortunately for

gaining the performance edge

Carbohydrates spare muscle protein by decreasing the body's reliance on gluconeogenesis to make its own carbohydrates.

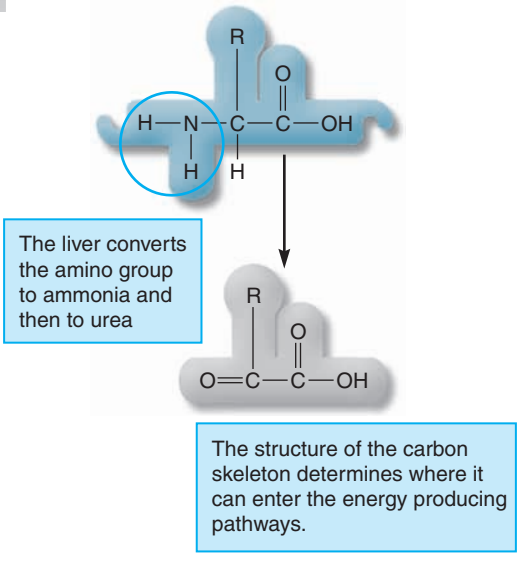


Figure 2.33 Deamination. A deamination reaction strips the amino group from an amino acid.

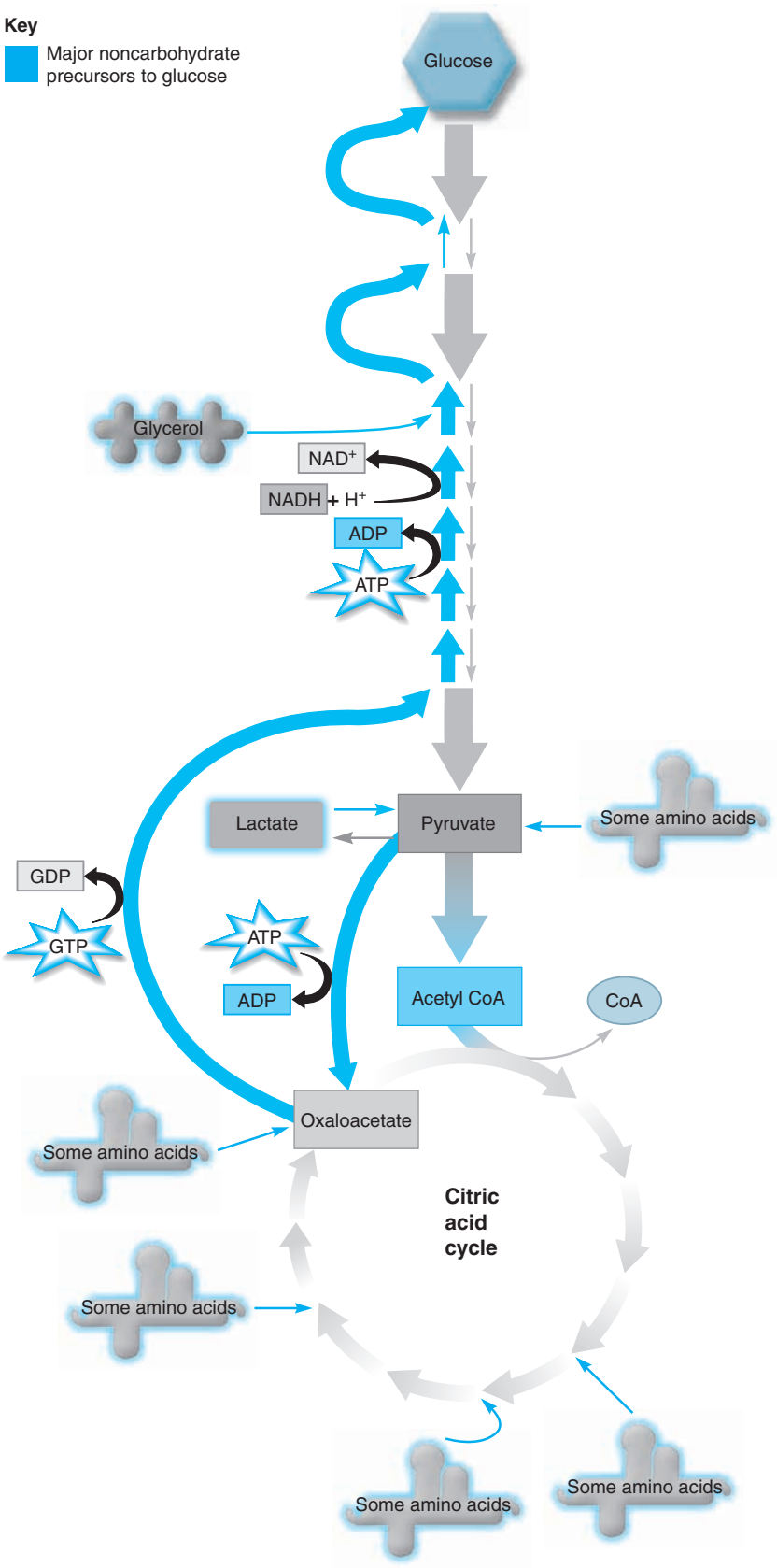


Figure 2.34 Gluconeogenesis. Liver and kidney cells make glucose from pyruvate by way of oxaloacetate. Gluconeogenesis is not the reverse of glycolysis. Although these pathways share many reactions, albeit in the reverse direction, gluconeogenesis must detour around the irreversible steps in glycolysis.

Food for Thought 2.2

Understanding Bioenergetics

In this exercise, your knowledge of how the energy systems work together to supply ATP during activity will be challenged.

the athlete, most of the proteins used in gluconeogenesis come from muscle.[10] This is one reason why carbohydrate intake is so important to the athlete. If carbohydrate intake is adequate to meet energy demands and carbohydrate stores are replenished after training, then proteins do not need to be converted to carbohydrates, and muscle protein is spared. The relationship between carbohydrate intake and protein breakdown for energy is a critical concept to understand. Put in other words, adequate carbohydrates in the diet spare muscle protein.

Food for Thought 2.3

You Are the Nutrition Coach

Apply the concepts from this chapter to several case studies.

The Box Score

Key Points of Chapter

- The digestive system is basically a long, internalized tube that passes through the body. Foods enter via the mouth and exit from the anus. Substances in the digestive system have not entered the body until they are absorbed across the intestinal wall.
- The anatomy of the digestive system includes the mouth, esophagus, stomach, small intestine, and large intestine. Associated structures, including the salivary glands, pancreas, liver, and gallbladder, secrete enzymes and bile salts that help in the digestive process.
- Digestion of carbohydrates begins in the mouth as a result of the mechanical process of mastication and the enzymatic actions of salivary amylase. However, the majority of digestion occurs in the small intestine, where the foodstuffs are subjected to the actions of various pancreatic and intestinal enzymes.
- During digestion, carbohydrates are broken down into their component parts, monosaccharides (i.e., simple sugars).
- Absorption of monosaccharides occurs in the small intestine via facilitated diffusion or active transport, depending on the type of sugar.
- Once the bloodborne simple sugars reach the cells of the liver, those that are not in the form of glucose (e.g., fructose) are converted to glucose. The glucose can then be stored as glycogen in the liver cells or released back into the bloodstream to be used for energy or stored by other cells of the body.
- Digestion of dietary fats begins in the mouth via mastication and the enzymatic actions of salivary lipase. The digestive process continues in the stomach through muscle actions of the stomach wall and the enzymatic actions of gastric lipase. However, the majority of fat digestion occurs in the small intestine, where various lipases act on the dietary fats (i.e., triglycerides), breaking them into free fatty acids and monoglycerides.
- Absorption of fats also occurs in the small intestine. The short- and medium-chain fatty acids are absorbed via passive diffusion and enter directly into the bloodstream. Long-chain fatty acids and monoglycerides are wrapped by bile salts to form micelles and carried to the intestinal wall, where the fats are released from the micelles and absorbed via passive diffusion. The absorbed fats from the micelles are resynthesized into triglycerides and packaged into chylomicrons. The chylomicrons are released from the cells and enter into the circulatory system via the lymph.
- Lipoprotein lipase, which is located on capillary walls and inside adipocytes, is the enzyme responsible for the entrance and exit of fats from the adipocytes.
- Fatty acids in the blood are transported into muscle cells via facilitated diffusion, whereas triglycerides in bloodborne chylomicrons are acted upon by lipoprotein lipase in the capillaries found in muscle. Lipoprotein lipase breaks down the triglycerides into fatty acids, which are then transported across the muscle cell membrane. Once inside the muscle cells, the fats can be stored or used for energy.
- During digestion, dietary proteins are broken into their basic building blocks, known as amino acids.
- Digestion of proteins begins in the mouth via mastication and continues in the stomach where they are denatured by hydrochloric acid. Once they leave the stomach, protease enzymes in the small intestine continue to break the proteins into single amino acids or small chains of two or three amino acids.
- The small digested protein remnants are absorbed via facilitated diffusion or active transport in the small intestine. Once inside the intestinal cells, any existing chains of amino acids are broken up into single amino acids and then released into the bloodstream.

- When ingested amino acids make it into the bloodstream, they become part of the body's amino acid pool. The amino acid pool also includes amino acids found in other tissues, primarily skeletal muscle and the liver. The blood, with its circulating levels of amino acids, makes up the central part of the amino acid pool, which remains in equilibrium with the other compartments. This helps to maintain the blood's levels of amino acids, thereby serving as a constant and readily available source of amino acids for the body.
- Amino acid absorption from the bloodstream into the cells of the body tissues occurs through facilitated diffusion. Once inside, the amino acids can be used to make needed proteins through the processes of transcription and translation. Genes in the nucleus are transcribed to form mRNA. The mRNA leaves the nucleus and is translated by ribosomes, which attach the amino acids together to form the specific protein required.
- Minerals, vitamins, and water do not need to be broken down into smaller units via digestion to be absorbed into the body.
- Digestion of food releases minerals and vitamins, thereby making them available for absorption. Most vitamins and minerals are absorbed in the small intestine. The exceptions are sodium, potassium, chloride, and some vitamin K, which are all absorbed in the large intestine.
- Without knowledge of the three energy systems and how they work together to supply energy during specific sports activities, the sports nutrition professional is severely disadvantaged with regard to creating an individualized dietary plan.
- Energy is an entity that is better explained or defined than shown because it has no shape, no describable features, and no physical mass. Energy enables athletes to perform physical work and is measured in kilocalories (kcals). All cellular and bodily functions require energy. The sum total of all the energy (i.e., total daily calories) required by the body to power cellular processes and activities is known as metabolism.
- Energy exists in six basic forms: chemical, nuclear, electrical, mechanical, thermal, and radiant. However, the form of energy that humans and animals directly rely upon for survival is chemical energy.
- The macronutrients—carbohydrates, fats, and proteins—are also known as the energy nutrients. The energy trapped in the bonds of macronutrients is used to make a high-energy compound known as adenosine triphosphate (ATP). ATP is the body's direct source of energy for all biological work. The role of the cellular metabolic factory is to release the chemical energy stored in the macronutrients and use it to make ATP.
- Energy metabolism or bioenergetics is the study of how energy is captured, transferred, and/or utilized within biological systems. The three energy systems responsible for production of ATP are the phosphagen, anaerobic, and aerobic systems. Each of these systems has unique characteristics, but they work together to supply the specific ATP needs of the athlete.
- The three energy systems are constantly working together to maintain the small ATP pools that exist in cells. Anywhere along the energy continuum, from rest to maximal physical movements, the three energy systems work together to maintain the ATP levels. ATP levels are never depleted in cells; if the energy systems cannot keep up with energy demand, fatigue occurs. The decrease in performance caused by fatigue lowers energy demand and enables the energy systems to prevent ATP depletion.
- To metabolize the energy nutrients and in the process make ATP, the cells must possess enzymes that sequentially break down the energy nutrients and in the process capture energy in the form of ATP. The enzymes for the phosphagen and anaerobic systems lie within the cytoplasm of the cell. The majority of enzymes and molecular compounds important to the aerobic system are found within specialized organelles known as mitochondria. As a result, mitochondria are sometimes referred to as the "aerobic powerhouses" of cells.
- Carbohydrates can be metabolized for energy both aerobically and anaerobically. In fact, carbohydrates are the only macronutrient that can be metabolized for energy via the anaerobic system. Fats and proteins can be metabolized only via the aerobic system. This is just one reason why carbohydrates are so important to athletes.
- The aerobic energy system is composed of five metabolic pathways, three of which are unique to each energy nutrient. Carbohydrates are metabolized via glycolysis, then the citric acid cycle, followed by the electron transport chain. Fats must go through beta-oxidation, then the citric acid cycle, and finally the electron transport chain. Proteins, which are not usually a major energy source, are first deaminated and then metabolized via the citric acid cycle and the electron transport chain.

Study Questions

1. What are the various anatomical components of the digestive system?
2. What are some of the similarities in the digestive processing of carbohydrates, fats, and proteins? How does digestion differ among them?
3. What are the four processes of cellular absorption?

4. Digestion breaks the macronutrients into their constituent parts so that they can be absorbed. What are the constituent parts of each macronutrient?
5. What is the difference between a micelle and a chylomicron?
6. What are the possible fates of the sugars, fats, and amino acids released into the bloodstream during the digestion of foods?
7. How do cells make proteins? Where are the instructions for protein synthesis found, and what processes are involved in making proteins?
8. What is energy? What are the various forms of energy? Which form is most important to human physiology?
9. What are the macronutrients? What role do they play with regard to supplying the body with energy?
10. What are the three energy systems? What are their characteristics with regard to rate of production and capacity to make energy?
11. What cellular organelle is called the "aerobic powerhouse" of the cell? Explain why.
12. An elite marathoner is at mile 17 in the race and bioenergetically in steady state. What energy systems are contributing to the athlete's energy needs? Which energy system is the major contributor?
13. What energy system is the major contributor of ATP during a discus throw?
14. An athlete is running an 800-meter race in a track meet. What energy systems are contributing to the athlete's energy needs? Which energy system is the major contributor of ATP?
15. What metabolic pathways are required to aerobically metabolize fats? Can fats be metabolized anaerobically?
16. Which energy system is also called the "immediate energy system"? What high-energy compounds make up this system?
17. Which compounds are known as hydrogen carriers and play a big role in transferring hydrogen ions to the electron transport chain?

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