

CHAPTER 4

Proteins

KEY CONCEPTS

- Protein in food provides the amino acids that are necessary for building and maintaining body tissue.
- Protein balance—both within the body and in the diet—is essential to life and health.
- The quality of a protein food and its ability to meet the body's needs are determined by the composition of amino acids.

Many different proteins in the body make human life possible. Each of these thousands of specific body proteins has a unique structure that is designed to perform an assigned task. Amino acids are the building blocks of all proteins. People obtain amino acids from a variety of foods. This chapter looks at the specific nature of proteins, both in food and in human bodies; it explains why protein balance is essential to life and health, and it discusses how that balance is maintained.

THE NATURE OF PROTEINS

Amino Acids: Basic Building Matter

Role as Building Units

All protein, whether in our bodies or in the food we eat, is composed of building blocks known as amino acids. Amino acids are joined in unique chain sequences to form specific proteins. Each amino acid is joined by a peptide bond (Figure 4-1). Two amino acids joined together are called a *dipeptide*. Polypeptides are chains of up to 100 amino acids. Hundreds of amino acids are linked together to form a single protein. When foods rich in protein are eaten, the protein is broken down into amino acids during the digestive process. The specific types of protein found in different foods are unique. For example, casein is the protein that is found in milk and cheese; albumin is in egg whites, and gluten is in wheat products. After they are absorbed into the body, amino acids are then reassembled in a specific order to form a variety of important body proteins. To maintain its solvency, each protein chain adopts a folded form, which can fold and unfold in accordance with metabolic need.

Because proteins are relatively large, complex molecules, they are occasionally subject to mutations or malformations in structure. For example, protein-folding mistakes are involved in Alzheimer's disease, which robs many older adults of their mental capacity.

Dietary Importance

Amino acids are named for their chemical nature. The word *amino* refers to compounds that contain nitrogen. Like carbohydrates and fats, proteins have a basic structure of carbon, hydrogen, and oxygen. However, unlike carbohydrates and fats, protein is approximately 16% nitrogen. As such, protein is the primary source of nitrogen in the diet. In addition, some proteins contain small but valuable amounts of the minerals sulfur, phosphorus, iron, and iodine.

Classes of Amino Acids

Twenty common amino acids have been identified, all of which are vital to life and health. These amino acids are classified as *indispensable*, *dispensable*, or *conditionally indispensable* in the diet according to whether the body

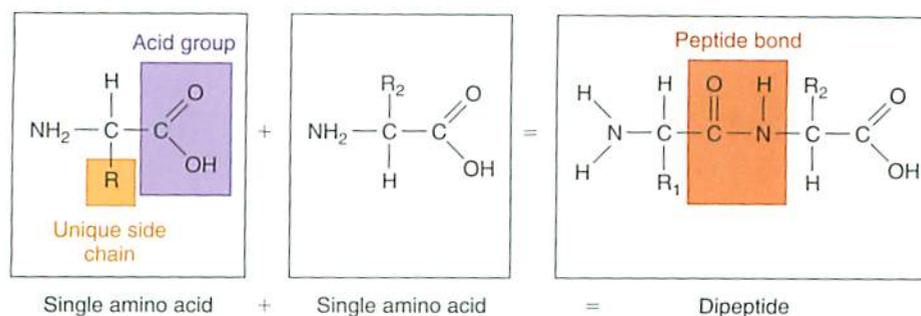


Figure 4-1 Amino acid structure. (Modified from Mahan LK, Escott-Stump S. *Krause's food & nutrition therapy*. 12th ed. Philadelphia: Saunders; 2008.)

can make them (Box 4-1).¹ These classifications were formerly known as *essential*, *nonessential*, or *conditionally essential*, respectively.

Indispensable Amino Acids

Nine amino acids are classified as indispensable because the body cannot manufacture them in sufficient quantity or at all (see Box 4-1). As the word *indispensable* implies, these amino acids are necessary in the diet and cannot be left out. Under normal circumstances, the remaining 11 amino acids are synthesized by the body to meet continuous metabolic demands throughout the life cycle.

Dispensable Amino Acids

The word *dispensable* can be confusing; all amino acids have essential tissue-building and metabolic functions in the body. However, the term refers to five amino acids that the body can synthesize from other amino acids, provided that the necessary building blocks and enzymes

BOX 4-1 INDISPENSABLE, DISPENSABLE, AND CONDITIONALLY INDISPENSIBLE AMINO ACIDS

INDISPENSIBLE	DISPENSABLE	CONDITIONALLY INDISPENSIBLE
Histidine	Alanine	Arginine
Isoleucine	Aspartic acid	Cysteine
Leucine	Asparagine	Glutamine
Lysine	Glutamic acid	Glycine
Methionine	Serine	Proline
Phenylalanine		Tyrosine
Threonine		
Tryptophan		
Valine		

are present (see Box 4-1). These amino acids are needed by the body for a healthy life, but they are dispensable (i.e., not necessary) in the diet.

Conditionally Indispensable Amino Acids

The remaining six amino acids are classified as *conditionally indispensable* (see Box 4-1). Under certain physiologic conditions, these amino acids, which are normally synthesized in the body (along with the dispensable amino acids), must be consumed in the diet. Arginine, cysteine, glutamine, glycine, proline, and tyrosine are indispensable when endogenous sources cannot meet the metabolic demands. For example, the human body can make cysteine from the essential amino acid methionine. However, when the diet is deficient in methionine, cysteine must be consumed in the diet, thereby making it an indispensable amino acid during that time. Severe physiologic stress, illness, and genetic disorders also may render an amino acid conditionally indispensable. Phenylketonuria is a genetic disorder in which the affected

indispensable amino acids the nine amino acids that must be obtained from the diet because the body does not make adequate amounts to support body needs.

dispensable amino acids the five amino acids that the body can synthesize from other amino acids that are supplied through the diet and thus do not have to be consumed on a daily basis.

conditionally indispensable amino acids the six amino acids that are normally considered dispensable amino acids because the body can make them; however, under certain circumstances (e.g., illness), the body cannot make them in high enough quantities, and they become indispensable to the diet.



DRUG-NUTRIENT INTERACTION

ASPARTAME AND PHENYLKETONURIA

Aspartame is a nonnutritive sweetener (i.e., it does not provide any nutrients or calories) that is composed of two amino acids: aspartic acid and phenylalanine. It is made synthetically, and its structure more closely resembles a protein than a carbohydrate. However, by adding a methanol group, the resulting product provides a sweet taste. It is used in foods and beverages as a high-potency sweetener, and it is approximately 200 times sweeter than table sugar or sucrose. Therefore, much less is needed to sweeten a food to the same degree.

As mentioned previously, phenylketonuria (PKU) is a disease in which an individual lacks the enzyme phenylalanine hydroxylase. Without this enzyme, phenylalanine cannot be metabolized and thus accumulates in the blood. High levels in the blood are toxic to brain tissue, and this can result in mental degradation and possibly death. Individuals with PKU must follow a strict diet with careful intake

of phenylalanine that supports growth but that does not exceed tolerance. Those with PKU should avoid all foods that contain aspartame because of its concentrated phenylalanine content.

Foods that contain phenylalanine, such as aspartame—which is also known by the trade names *NutraSweet* and *Equal*—have warnings on their packages for PKU patients.

Following is a list of common foods that contain aspartame:

- Chewing gum
- Diet sodas
- Frozen desserts
- Gelatins
- Puddings
- Sugar-free candies
- Yogurt

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individual lacks the enzyme that is needed to convert phenylalanine to tyrosine. Because the conversion of phenylalanine cannot take place, amounts in the blood may rise to toxic levels. A specific phenylketonuria diet must be followed and certain foods avoided (see the Drug-Nutrient Interaction box, “Aspartame and Phenylketonuria”). With this condition, tyrosine must be supplied by the diet, and thus it is conditionally indispensable.

Balance

In terms of nutrition, the term *balance* refers to the relative intake and output of substances in the body to maintain the equilibrium that is necessary for health in various circumstances throughout the lifespan. This concept of balance can be applied to life-sustaining protein and the nitrogen that it supplies.

Protein Balance

The body’s tissue proteins are constantly being broken down into amino acids through a process called *catabolism*, and they are then resynthesized into tissue proteins as needed through a process called *anabolism*. To maintain nitrogen balance, the part of the amino acid that contains nitrogen may be removed by a process called *deamination*, converted into ammonia, and then excreted as urea in the urine. The remaining nonnitrogen residue will be used to make carbohydrate or fat, or it may be reattached to make another amino acid, if

necessary. The rate of this protein and nitrogen turnover varies in different tissues in accordance with the degree of metabolic activity and the available supply of amino acids.

Tissue turnover is a continuous process of reshaping, building, and adjusting to maintain overall protein balance within the body. The body maintains a delicate balance among tissue protein, plasma protein, and dietary protein. With this finely balanced system, healthy individuals have a small pool of amino acids from both tissue protein and dietary protein that is available to meet metabolic needs (Figure 4-2).

Nitrogen Balance

The body’s nitrogen balance indicates how well its tissues are being maintained. The intake and use of dietary protein are measured by the amount of nitrogen intake in food protein and the amount of nitrogen excreted in the urine. For example, 1 g of urinary nitrogen results from the digestion and metabolism of 6.25 g of protein. Thus, if 1 g of nitrogen is excreted in the urine for every 6.25 g of protein consumed, then the body is said to be in nitrogen balance. This balance is the normal pattern in adult health. However, at different times of life or in states of malnutrition or illness, the balance may shift to be either positive or negative.

Positive Nitrogen Balance. A positive nitrogen balance exists when the body holds on to more nitrogen than it excretes, thus storing more nitrogen (by building tissue) than it is losing (by breaking down

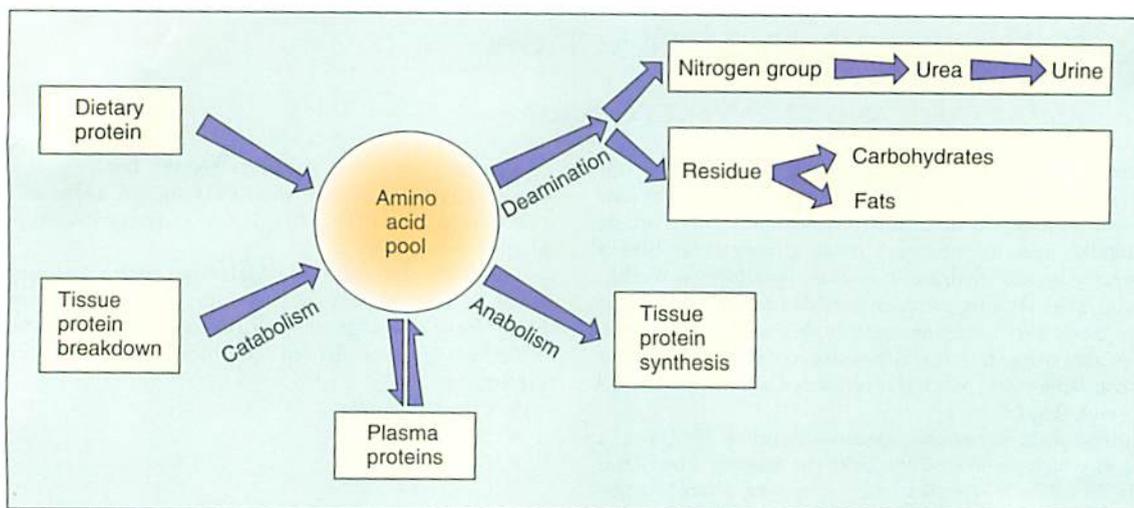


Figure 4-2 The balance between protein compartments and the amino acid pool.

tissue). This situation occurs normally during periods of rapid growth, such as infancy, childhood, adolescence, pregnancy, and lactation. A positive nitrogen balance also occurs in individuals who have been ill or malnourished and who are being “built back up” with increased nourishment. In such cases, protein is used to meet increased needs for tissue building and its associated metabolic activity.

Negative Nitrogen Balance. A negative nitrogen balance occurs when the body holds on to less nitrogen than it excretes. This means that the body has an inadequate protein intake and is losing nitrogen by breaking down more tissue than it is building up. This situation arises in states of malnutrition and illness. For example, negative nitrogen balance is seen in individuals when protein deficiency—even when kilocalories from carbohydrate and fat are adequate—causes the classic protein deficiency disease kwashiorkor. The failure to maintain the nitrogen balance may not become apparent for some time, but it eventually causes the loss of muscle tissue, the impairment of body organs and functions, and an increased susceptibility to infection. In children, negative nitrogen balance for an extended period causes growth retardation and may be fatal.

FUNCTIONS OF PROTEIN

Primary Tissue Building

Protein is the fundamental structural material of every cell in the body. In fact, the largest dry-weight portion of

the body is protein. Body protein (e.g., the lean mass of muscles) accounts for approximately three fourths of the dry matter in most tissues, excluding bone and adipose tissue. Protein makes up the bulk of the muscles, internal organs, brain, nerves, skin, hair, and nails, and it is also a vital part of regulatory substances such as enzymes, hormones, and blood plasma. All such tissues must be constantly repaired and replaced. The primary functions of protein are to repair worn-out, wasted, or damaged tissue and to build new tissue. Thus, protein meets growth needs and maintains tissue health during the adult years. In fact, protein is central to the biochemical machinery that makes cells work.

Additional Body Functions

In addition to its basic tissue-building function, protein has other body functions related to energy, water balance, metabolism, and the body’s defense system. Box 4-2 lists the major functions of protein.

Water and pH Balance

Fluids within the body are divided into three compartments: intravascular, intracellular, and interstitial (see Chapter 9). The body compartments are separated with cell membranes that are not freely permeable to protein. Because water is attracted to protein, plasma proteins such as albumin help to control water balance throughout the body by exerting osmotic pressure. This pressure maintains the normal circulation of tissue fluids within the appropriate compartments.

BOX 4-2 FUNCTIONS OF PROTEIN

- Structural tissue building
- Water balance through osmotic pressure
- Digestion and metabolism through enzymatic action
- Cell signaling (hormones) and transport (hemoglobin and transferrin)
- Immunity (antibodies)
- Source of energy (4 kcal/g)

The normal pH of blood is between 7.35 and 7.45. However, constantly occurring bodily functions release acidic and alkaline substances, thereby affecting the overall acidity and alkalinity of blood. The unique structure of proteins—a combination of a carboxyl acid group and a base group—allows them to act as buffering agents by releasing or taking up excess acid within the body. If blood reaches a pH in either extreme (i.e., too acidic or too alkaline), plasma proteins denature and can result in death.

Metabolism and Transportation

Protein aids metabolic functions through enzymes, transport agents, and hormones. Digestive and cell enzymes are proteins that control metabolic processes. Enzymes that are necessary for the digestion of carbohydrates (amylase), fats (lipase), and proteins (proteases) are all proteins in structure. Protein also acts as the vehicle in which nutrients are carried throughout the body. Lipoproteins are necessary to transport fats in the water-soluble blood supply. Other examples are hemoglobin, which is the vital oxygen carrier in the red blood cells, and transferrin, which is the iron transport protein in blood. Peptide hormones (e.g., insulin, glucagon) are also proteins that play a major function in the metabolism of glucose (see Chapter 20).

Body Defense System

Protein is used to build special white blood cells (i.e., lymphocytes) and antibodies as part of the body's immune system to help defend against disease and infection.

Energy System

As described in previous chapters, carbohydrates are the primary fuel source for the body's energy system, and they are assisted by fat as a stored fuel. In times of need, protein may furnish additional fuel to sustain body heat and energy, but this is a less-efficient backup source for use only when the supply of carbohydrate and fat is insufficient. The available fuel factor of protein is 4 kcal/g.

FOOD SOURCES OF PROTEIN**Types of Food Proteins**

Fortunately most foods contain a mixture of proteins that complement one another. In a mixed diet, animal and plant foods provide a wide variety of many nutrients, including protein. Thus, the key to a balanced diet is variety. Food proteins are classified as complete or incomplete proteins, depending on their amino acid composition.

Complete Proteins

Protein foods that contain all nine indispensable amino acids in sufficient quantity and ratio to meet the body's needs are called *complete proteins*. These proteins are primarily of animal origin (e.g., egg, milk, cheese, meat, poultry, fish; Figure 4-3). However, soybeans and soy products are the exception. Soy products are the only plant sources of complete proteins. Another exception is gelatin, which is an incomplete animal protein. Although gelatin is a protein of animal origin, it is a relatively insignificant protein, because it lacks the three essential amino acids tryptophan, valine, and isoleucine, and it has only small amounts of leucine.

Incomplete Proteins

Protein foods that are deficient in one or more of the nine indispensable amino acids are called *incomplete proteins*. These proteins are generally of plant origin (e.g., grains, legumes, nuts, seeds), but they are found in foods that make valuable contributions to the total amount of dietary protein.

Vegetarian Diets**Complementary Protein**

Current knowledge of protein metabolism and the pooling of amino acid reserves (see Figure 4-2) indicates that a mixture of plant proteins can provide adequate amounts of amino acids when the basic use of various grains is expanded to include soy protein and other dried legume proteins (i.e., beans and peas). Because most plant proteins are incomplete and thereby lacking one or more of the indispensable (or essential) amino acids, vegetarians can mix plant foods so that the amino acids missing in one food are supplied by another. This is the art of combining plant protein foods so that they complement one another and supply all nine indispensable amino acids.

A normal eating pattern throughout the day, together with the body's small reserve of amino acids, usually ensures an overall amino acid balance. The underlying

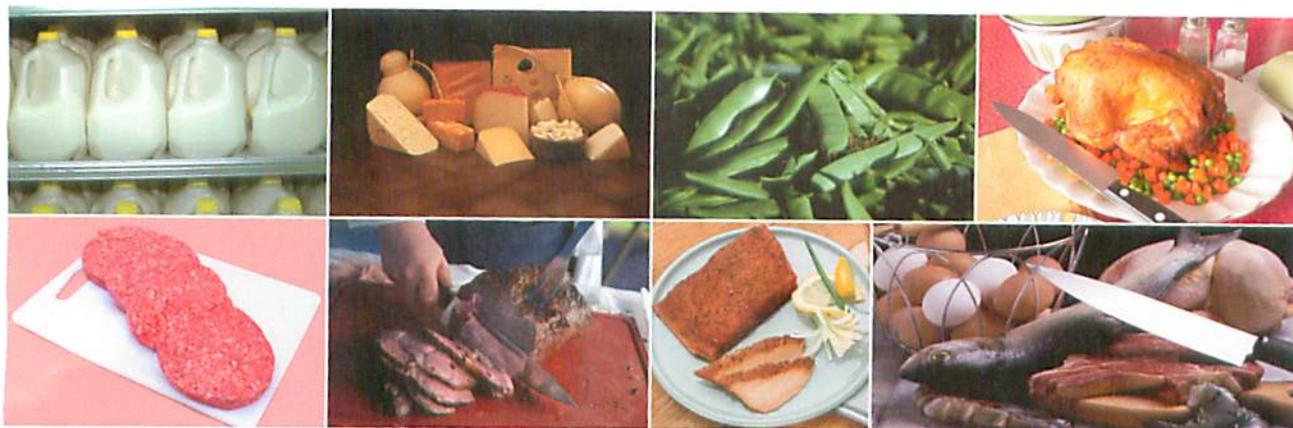


Figure 4-3 Sources of complete proteins. (Copyright JupiterImages Corp.)



CULTURAL CONSIDERATIONS

INDISPENSABLE AMINO ACIDS AND THEIR COMPLEMENTARY FOOD PROTEINS

A large percentage of the worldwide population follows various forms of vegetarian diets for religious, traditional, or economic reasons. Seventh-Day Adventists follow a lacto-ovo-vegetarian diet, whereas individuals of the Hindu and Buddhist faith generally are lacto-vegetarian. The Mediterranean diet has such a strong emphasis on grains, pastas, vegetables, and cheese that few other animal products (i.e., beef, chicken, and fish) are consumed. In other areas of the world, the economic burden of animal products does not allow for the consumption of such foods. Any form of a vegetarian diet can be healthy; however, a good understanding of how to achieve complete protein balance is necessary.

All nine indispensable (or essential) amino acids must be supplied by the diet. Protein from both animal and plant sources can meet protein requirements. One concern related to a vegetarian diet is getting a balanced amount of the indispensable amino acids to complement each other and to make complete protein combinations.

When making complementary food combinations to balance the needed amino acids, families of foods (e.g.,

grains, legumes, dairy) must be mixed. For example, grains are low in threonine and high in methionine, whereas legumes are the opposite and as such are low in methionine and high in threonine. Therefore, grains and legumes help to balance one another with regard to the accumulation of all indispensable amino acids. The addition of milk products and eggs enhances the amino acid adequacy of lacto-ovo-vegetarians. Following are sample food combinations to illustrate complementary protein combinations:

- *Grains and peas, beans, or lentils*: brown rice and beans; whole-grain bread with pea or lentil soup; wheat or corn tortilla with beans; peanut butter on whole wheat bread; Indian dishes of rice and dal (a legume); Chinese dishes of tofu and rice
- *Legumes and seeds*: falafel; soybeans and pumpkin or sesame seeds; Middle Eastern hummus (garbanzo beans and sesame seeds) or tahini
- *Grains and dairy*: whole-wheat pasta and cheese; yogurt and a multigrain muffin; cereal and milk; a cheese sandwich made with whole-grain bread

requirement for vegetarians—as for all people—is to eat a sufficient amount of varied foods to meet normal nutrient and energy needs (see the Cultural Considerations box, “Indispensable Amino Acids and Their Complementary Food Proteins”).

Types of Vegetarian Diets

Vegetarian diets differ according to the beliefs or needs of the individuals who are following such food patterns. Approximately 2.3% of the U.S. adult population (roughly

4.9 million people) consistently followed a vegetarian diet in 2006.² A variety of reasons lead people to choose a vegetarian diet, including environmental and animal cruelty concerns, health incentives, religious adherence (e.g., Buddhists, Hindus, Seventh-Day Adventists), and aversion to the consumption of animal products. Alternatively, a diet that is void of animal products is not always a choice. In some areas in the world, vegetarianism is simply a result of the lack of resources and availability of animal products.

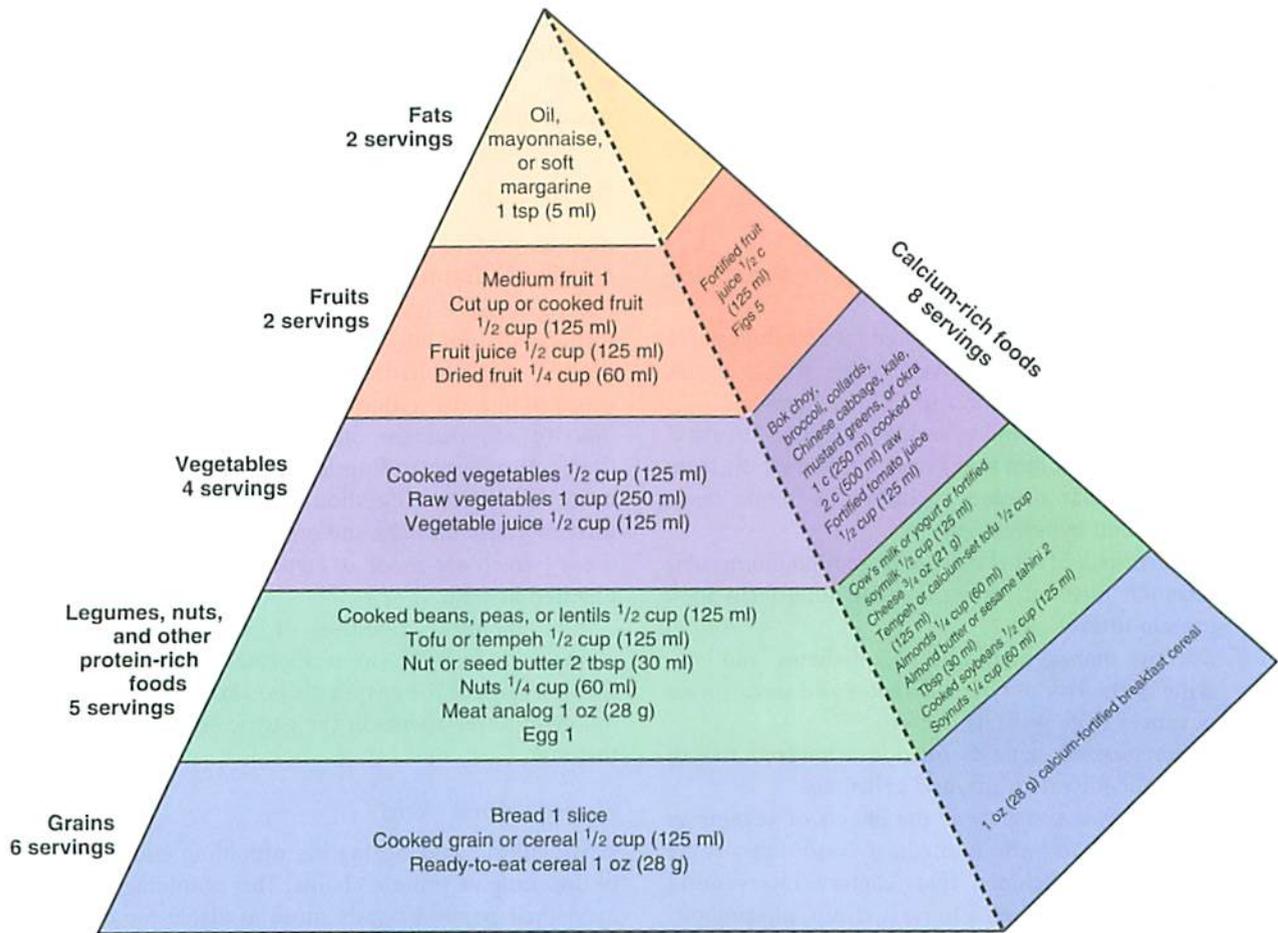


Figure 4-4 The lacto-ovo-vegetarian diet pyramid. (Reprinted from Messina V, Melina V, Mangels AR. A new food guide for North American vegetarians. *J Am Diet Assoc.* 2003; 103(6):771-775.)

In general, vegetarians can be described as one of the following four basic types:

- 1. Lacto-ovo-vegetarians:** These are vegetarians who follow a food pattern that allows for the consumption of dairy products and eggs (Figure 4-4). Their mixed diet of plant and animal food sources that excludes meat, poultry, pork, and fish poses no nutritional concerns.
- 2. Lacto-vegetarians:** These vegetarians accept only dairy products from animal sources to complement their basic diet of plant foods. The use of milk and milk products (e.g., cheese) with a varied mixed diet of whole or enriched grains, legumes, nuts, seeds, fruits, and vegetables in sufficient quantities to meet energy needs provides a balanced diet.
- 3. Ovo-vegetarians:** The only animal foods included in the ovo-vegetarian diet are eggs. Because eggs are an excellent source of complete proteins,

individuals who are following this diet do not have to be overly concerned with complementary proteins if eggs are consumed consistently.

- 4. Vegans:** Vegans follow a strict vegetarian diet and consume no animal foods. Their food pattern consists entirely of plant foods (e.g., whole or enriched grains, legumes, nuts, seeds, fruits, vegetables). The use of soybeans, soy milk, soybean curd (tofu), and processed soy protein products enhances the nutritional value of the diet. Careful planning and sufficient food intake ensure adequate nutrition.

The most recent position paper from the Academy of Nutrition and Dietetics (formerly known as the American Dietetic Association) and Dietitians of Canada states that a vegetarian diet (including the vegan option) can meet the current recommendations for all essential nutrients, including protein.³ The experts also indicate that the former mindful combination of complementary plant

proteins within every given meal is unnecessary; achieving a balance throughout the day is more important. In addition, vegetarian diets are appropriate throughout all stages of life, including pregnancy, infancy, childhood, adolescence, and older age as well as for those with an athletic lifestyle.

Health Benefits and Risk

Some of the most notable benefits of vegetarianism include the following^{3,4}:

- Lower levels of dietary saturated fat and cholesterol
- Higher intake of fruits, vegetables, whole grains, nuts, soy products, fiber, and phytochemicals
- Lower body mass index and prevalence of obesity
- Better lipid profiles and lower rates of death from cardiovascular disease, including ischemic heart disease and hypertension
- Lowered risk of renal disease from high glomerular filtration rates as compared with long-term high protein intake
- Effective management of type 2 diabetes⁵ and lowering of the risk of type 2 diabetes and some forms of cancer (e.g., prostate, colon)
- Other possible benefits include a lowered risk of dementia, diverticulitis, and gallstones

After an extensive review of the effects of vegetarian diets with regard to various medical conditions, some researchers have concluded that “dietary intervention with a vegetarian diet seems to be a cheap, physiologic, and safe approach for the prevention and possible management of modern lifestyle diseases.”⁶ The preventive mechanism at work in the vegetarian diet is the rich supply of monounsaturated and polyunsaturated fatty acids, fiber, complex carbohydrates, and antioxidants and a restriction of saturated fat. To reap the benefits of a vegetarian diet, a well-balanced diet from a variety of foods is necessary. It should be noted that not all vegetarians follow an ideal well-balanced diet and therefore do not obtain the possible health benefits.

Key nutrients of concern for practicing vegetarians are protein, iron, zinc, calcium, vitamin D, vitamin B₁₂, and omega-3 fatty acids.^{3,7} Reasons for concern and effective ways to overcome these barriers are outlined in Table 4-1.

DIGESTION OF PROTEINS

Mouth

After a food that contains protein is consumed, the protein must be broken down into the necessary ready-to-use building blocks: amino acids. This is done through the successive parts of the gastrointestinal tract by

mechanical and chemical digestion. The mechanical breaking down of protein begins with chewing in the mouth. The food particles are mixed with saliva and passed on to the stomach as a semisolid mass.

Stomach

Because proteins are such large and complex structures, a series of enzymes is necessary for digestion and for the release of individual amino acids, which is the primary form needed for absorption. Unlike the enzymes that are needed for carbohydrate and fat digestion, all enzymes involved in protein digestion (i.e., proteases) are stored as inactive **proenzymes** called **zymogens**. Zymogens are then activated according to need. The enzymes that are needed for protein digestion cannot be stored in an active form, because the cells and organs that produce and store them (which are made of structural proteins) would be digested as well.

The chemical digestion of protein begins in the stomach. In fact, the stomach’s chief digestive function is the first stage of the enzymatic breakdown of protein. The following three agents in the gastric secretions help with this task.

Hydrochloric Acid

Hydrochloric acid begins the unfolding and denaturing of the complex protein chains. This unfolding makes the individual peptide bonds more available for enzymatic action. Hydrochloric acid also provides the acid medium that is necessary to convert pepsinogen into active **pepsin**, which is the gastric enzyme that is specific to proteins.

Pepsin

Pepsin is first produced as an inactive proenzyme called *pepsinogen* by a single layer of chief cells in the stomach wall. The hydrochloric acid within gastric juices then changes pepsinogen to the active enzyme pepsin.

proenzyme an inactive precursor (i.e., a forerunner substance from which another substance is made) that is converted to the active enzyme by the action of an acid, another enzyme, or other means.

zymogen an inactive enzyme precursor.

pepsin the main gastric enzyme specific for proteins; pepsin begins breaking large protein molecules into shorter chain polypeptides, and it is activated by gastric hydrochloric acid.

TABLE 4-1 NUTRIENT CONSIDERATIONS FOR VEGETARIANS

Nutrient	Problem	Solution
Protein	Plant protein quality varies; lower bioavailability than animal protein	Consume a variety of plant foods throughout the day, including soy products
Iron	Plant foods contain nonheme iron, which is less bioavailable than the heme iron found in animal foods and which is sensitive to inhibitors such as phytate, calcium, tea, coffee, and fiber	Iron intake recommendations are 1.8 times higher than for nonvegetarians; consume high-iron plant foods with dietary sources of vitamin C, which is an enhancer of iron absorption
Zinc	Plant foods high in phytates bind zinc	Regularly consume foods such as nuts, soy products, zinc-fortified cereals, and soaked and sprouted beans, grains, and seeds
Calcium	Oxalates reduce the absorption of calcium found in spinach, beet greens, and Swiss chard	Regularly consume plant foods that are high in calcium and low in oxalates, such as Chinese cabbage, broccoli, Napa cabbage, collards, kale, okra, and turnip greens in addition to calcium-fortified foods such as orange juice
Vitamin D	Other than endogenously produced vitamin D from sunlight exposure, the primary source of this vitamin is fortified cow's milk	Sun exposure to the face, hands, and forearms for 5 to 15 minutes per day during the summer provides enough sunlight for light-skinned people to produce adequate amounts of vitamin D, and dark-skinned people require more sun exposure; otherwise, choose foods or dietary supplements that are fortified with vitamin D, such as soy milk, rice milk, orange juice, and breakfast cereal
Vitamin B ₁₂	No plant food contains active vitamin B ₁₂	Choose foods that are fortified with B ₁₂ , such as soy milk, breakfast cereal, nutritional yeast, or use dietary supplements
Omega-3 fatty acid (alpha-linolenic)	Few plant foods are good sources of alpha-linolenic acid	Regularly include sources of alpha-linolenic acid in the diet, such as flaxseeds, walnuts, canola oil, soy products, and breakfast bars fortified with DHA, or take DHA supplements that are derived from microalgae

Adapted from Craig WJ. Health effects of vegan diets. *Am J Clin Nutr.* 2009; 89(5):1627S-1633S; and Craig WJ, Mangels AR. Position of the American Dietetic Association: vegetarian diets. *J Am Diet Assoc.* 2009; 109(7):1266-1282.

Pepsin begins splitting the bonds between the protein's amino acids, which changes the large protein into short chains called *polypeptides*. If the protein were held in the stomach longer, pepsin could continue this breakdown until only the individual amino acids of the protein remained. However, with the normal gastric emptying time, pepsin only completes the first stage of breakdown.

Rennin

The gastric enzyme **rennin** is only present during infancy and childhood, and it is especially important for the infant's digestion of milk. Rennin and calcium act on the casein of milk to produce a curd. By coagulating milk into a more solid curd, rennin prevents the food from passing too rapidly from the infant's stomach to the small intestine.

Small Intestine

Protein digestion begins in the acidic medium of the stomach, and it is completed in the alkaline medium of

the small intestine. Enzymes from the secretions of both the pancreas and the intestine take part in this process.

Pancreatic Secretions

The following three enzymes produced by the pancreas continue breaking down proteins into more and more simple substances:

1. **Trypsin**, which is secreted first as inactive trypsinogen, is activated by the enzyme **enterokinase**. Enterokinase is secreted from the intestinal cells on contact with food entering the duodenum, which is the first section of the small intestine. The active trypsin then works on proteins and large polypeptide fragments that are carried from the stomach. This enzymatic action produces small polypeptides and dipeptides.
2. **Chymotrypsin**, which is secreted first as the inactive chymotrypsinogen, is activated by trypsin that is already present in the gut. The active enzyme then continues the same protein-splitting action of trypsin.

- 3. Carboxypeptidase** attacks the acid (i.e., carboxyl) end of the peptide chains, thereby producing small peptides and some free amino acids. Carboxypeptidase is also first released as an inactive proenzyme (procarboxypeptidase), and it is activated by trypsin.

Intestinal Secretions

Glands in the intestinal wall produce the following two protein-splitting enzymes to complete the breakdown and free the remaining amino acids:

- 1. Aminopeptidase** attacks the nitrogen-containing (i.e., amino) end of the peptide chain and releases amino acids one at a time, thereby producing peptides and free amino acids.
- 2. Dipeptidase**, which is the final enzyme in the protein-splitting system, completes the job by breaking the remaining dipeptides into two free amino acids.

This finely coordinated system of protein-splitting enzymes breaks down the large, complex proteins into progressively smaller peptide chains and frees each individual amino acid. This is a tremendous overall task. The free amino acids are now ready to be absorbed directly into the portal blood circulation for use in the building of body tissues. This remarkable system of protein digestion is summarized in Figure 4-5.

RECOMMENDATIONS FOR DIETARY PROTEIN

Influential Factors of Protein Needs

The following three factors influence the body's requirement for protein: (1) tissue growth; (2) the quality of the dietary protein; and (3) the additional needs that result from illness or disease.

Tissue Growth

During rapid growth periods of the human life cycle, more protein per unit of body weight is necessary to build new tissue and to maintain present tissue. Human growth is most rapid during fetal growth, infant growth during the first year of life, and adolescent growth. Childhood is a sustained time of continued growth, but this occurs at a somewhat slower rate. For adults, protein requirements level off to meet tissue-maintenance needs, but individual needs may vary.

Dietary Protein Quality

The nature of a protein and its pattern of amino acids significantly influence its dietary quality.⁸ Sufficient

energy intake—especially from nonprotein foods—is necessary to conserve protein for tissue structure. In addition, the digestion and absorption of the protein consumed are affected by the complexity of its structure as well as its preparation and cooking. The comparative quality of protein foods has been determined by the following methods:

- 1. Chemical score**, which is derived from the amino acid pattern of the food; a high-quality protein food, such as an egg (with a value of 100), is compared with other foods according to their amino acid ratios
- 2. Biological value**, which is based on nitrogen balance
- 3. Net protein utilization**, which is based on the biological value and the degree of the food protein's digestibility

rennin the milk-curdling enzyme of the gastric juice of human infants and young animals (e.g., calves); rennin should not be confused with renin, which is an important enzyme produced by the kidneys that plays a vital role in the activation of angiotensin.

trypsin a protein-splitting enzyme secreted as the inactive proenzyme trypsinogen by the pancreas and that is activated and works in the small intestine to reduce proteins to shorter-chain polypeptides and dipeptides.

enterokinase an enzyme produced and secreted in the duodenum in response to food entering the small intestine; it activates trypsinogen to its active form of trypsin.

chymotrypsin a protein-splitting enzyme secreted as the inactive zymogen chymotrypsinogen by the pancreas; after it has been activated by trypsin, it acts in the small intestine to continue breaking down proteins into shorter-chain polypeptides and dipeptides.

carboxypeptidase a specific protein-splitting enzyme secreted as the inactive zymogen procarboxypeptidase by the pancreas; after it has been activated by trypsin, it acts in the small intestine to break off the acid (i.e., carboxyl) end of the peptide chain, thereby producing smaller-chained peptides and free amino acids.

aminopeptidase a specific protein-splitting enzyme secreted by glands in the walls of the small intestine that breaks off the nitrogen-containing amino end (i.e., NH₂) of the peptide chain, thereby producing smaller-chained peptides and free amino acids.

dipeptidase the final enzyme in the protein-splitting system that produces the last two free amino acids.

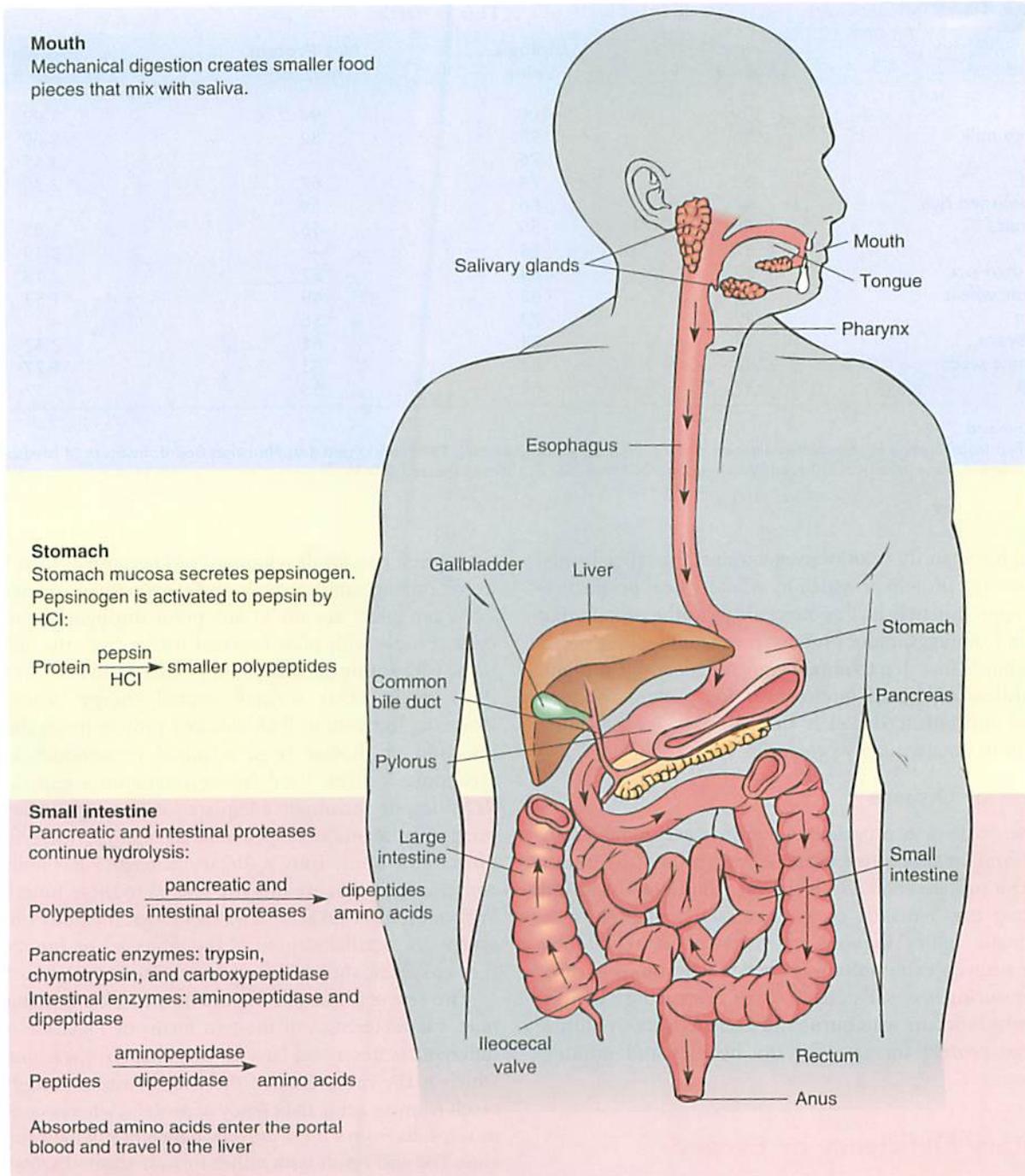


Figure 4-5 Summary of protein digestion. (Courtesy Rolin Graphics.)

4. *Protein efficiency ratio*, which is based on the weight gain of a growing test animal in relation to its protein intake

Table 4-2 compares various protein food scores on the basis of protein quality. As seen in the table, egg and cow's

milk proteins have the highest protein quality score. The quality and digestibility of most plant proteins are significantly lower than those of animal proteins. Therefore, the dietary protein needs of vegans who rely solely on plant foods of lower protein quality (e.g., cereal, legumes) may

TABLE 4-2 COMPARATIVE PROTEIN QUALITY OF SELECTED FOODS

Food	Chemical Score*	Biologic Value	Net Protein Utilization	Protein Efficiency Ratio
Egg	100	100	94	3.92
Cow's milk	95	93	82	3.09
Fish	71	76	—	3.55
Beef	69	74	67	2.30
Unpolished rice	67	86	59	—
Peanuts	65	55	55	1.65
Oats	57	65	—	2.19
Polished rice	57	64	57	2.18
Whole wheat	53	65	49	1.53
Corn	49	72	36	—
Soybeans	47	73	61	2.32
Sesame seeds	42	62	53	1.77
Peas	37	64	55	1.57

*Amino acid.

Modified from Guthrie H. *Introductory nutrition*. 6th ed. New York: McGraw-Hill; 1986; and Food and Nutrition Board, Institute of Medicine. *Recommended dietary allowances*. 10th ed. Washington, DC: National Academies Press; 1989.

be higher than those of nonvegetarians.³ In other words, because the protein provided by whole-wheat products is only approximately half as bioavailable as the protein that comes from eggs, more protein from whole-wheat products should be eaten to obtain equivalent useable protein. Regardless of dietary preferences for protein foods, a varied and balanced diet is the best way for a healthy person to obtain quality protein.

Illness or Disease

Illness or disease, especially when it is accompanied by fever and catabolic tissue breakdown, raises the body's need for protein and kilocalories for rebuilding tissue and meeting the demands of an increased metabolic rate. Traumatic injury requires extensive tissue rebuilding. After surgery, extra protein is needed for wound healing and restoring losses. Extensive tissue destruction, such as that which occurs with burns and pressure sores, requires a large protein increase for the healing and grafting processes.

Dietary Deficiency or Excess

As with any nutrient, moderation and balance are the keys to health. Too much or too little dietary protein can be problematic for overall body function.

Protein-Energy Malnutrition

Protein-energy malnutrition (PEM) may occur in a variety of situations. The most severe cases are found in less-industrialized countries where all foods—not just protein-rich foods—are in short supply. Children are at

the highest risk for developing PEM because of their high needs during rapid growth and development. However, PEM can affect anyone at any point throughout the life cycle. People with poor nutrient intake (e.g., the elderly, those with eating disorders) may suffer from PEM as well. PEM rarely exists without overall energy deficiency. However, individuals with elevated protein needs during infection or disease (e.g., acquired immunodeficiency syndrome, cancer, liver failure) sometimes experience PEM despite seemingly adequate total energy intake. As previously mentioned, protein has many critical functions in the body. Thus, a dietary deficiency has multiple consequences that are directly related to these functions. Without the amino acid building blocks, the body cannot synthesize needed structural (i.e., muscle) or functional (i.e., enzymes, antibodies, and hormones) proteins.

Two severe forms of PEM are kwashiorkor and marasmus. Characteristics of the two forms of PEM are quite different, as described later in this chapter. Kwashiorkor, which is the more fatal of the two forms, is thought to result from an acute deficiency of protein, whereas marasmus results from a more chronic deficiency of many nutrients. The end result with either form is stunted growth, a weakened immune system, and poor development.

Kwashiorkor. Kwashiorkor is more common among children who are between the ages of 18 and 24 months, who have been breastfed all their lives, and who are then rapidly weaned, often because of the arrival of a younger sibling. These children are switched from nutritionally balanced breast milk to a dilute diet of mostly carbohydrates and little protein. The children may receive adequate total kilocalories, but they lack enough bioavailable protein

sources. The term *kwashiorkor* is a Ghanaian word that refers to the disease that takes over the first child when the second child is born. Characteristics of kwashiorkor include generalized edema and fatty liver as a result of inadequate protein intake to maintain fluid balance and to transport fat from the liver (Figure 4-6).

To date, the exact pathogenesis of kwashiorkor is not well defined, and there may be additional factors involved in the development of the characteristic edema, such as oxidative stress and/or inappropriate antidiuretic hormone response.⁹

Marasmus. Individuals with marasmus have an emaciated appearance with little or no body fat. This is a chronic form of energy and protein deficiency; in other words, it is a result of basic starvation. Stunted growth and development are more severe with this form of PEM. Marasmus can affect individuals of all ages with inadequate food sources.

Excess Dietary Intake

Contrary to popular belief, one can ingest too much dietary protein. The body has a finite need for protein. When a person has met the dietary protein needs, additional



Figure 4-6 Kwashiorkor. The infant shows generalized edema, which is seen in the form of puffiness of the face, arms, and legs. (Reprinted from Kumar V, Abbas AK, Fausto N, Mitchell R. *Robbins basic pathology*. 8th ed. Philadelphia: Saunders; 2007.)

protein is deaminated (i.e., the nitrogen is removed) and stored as fat or used as energy. Eating excess protein does not build muscle; only exercising with enough protein to support growth can do that. The following problems can occur with diets that are heavily laden with protein:

1. They are often high in saturated fat, which is a known risk for cardiovascular disease.
2. If a person fills up on protein foods, little room is left for fruits, vegetables, and other whole grains, which are packed with essential vitamins, minerals, and fiber (see the Further Focus box, “The High-Protein Diet”).
3. The kidneys have the extra burden of getting rid of excess nitrogen.

Although most protein and amino acid supplements are not harmful in small doses, they are unnecessary in a balanced diet. However, taking excessive single amino acid dietary supplements can be harmful if it is to the exclusion of other essential amino acids, thereby creating an overall imbalance.

Dietary Guides

Dietary Reference Intakes

The Recommended Dietary Allowances (RDAs) continue to be the principal dietary guide for protein consumption, and they are part of the Dietary Reference Intake standards. Similar to carbohydrate and fat recommendations, the Dietary Reference Intakes for proteins have been set as a percentage of the total kilocalorie consumption by the National Academy of Sciences. Children and adults should obtain 10% to 35% of their total caloric intake from protein. The RDA standards relate to the age, sex, and weight of the average person, and they are based on the analysis of available nitrogen-balance studies. The RDA for both men and women is set at 0.8 g of high-quality protein per kilogram of desirable body weight per day¹ (i.e., 0.8 g/kg per day; see the Clinical Applications box, “Calculating Dietary Reference Intake for Protein”). Dietary recommendations are higher for infants and for pregnant and breastfeeding women in order to meet metabolic needs.

The RDAs are set to meet the nutritional requirements of most healthy people. Severe physical stress (e.g., illness, disease, surgery) can increase a person’s requirement for protein. Of note is that the U.S. Department of Agriculture’s “What We Eat in America” report found that the average daily protein intake of men and women 20 years and older is 101.9 g and 70.1 g per day, respectively.¹⁰ According to this report, men consume approximately 181% of their Dietary Reference Intakes for protein, and



FOR FURTHER FOCUS

THE HIGH-PROTEIN DIET

The per-capita consumption of protein by Americans continues to rise, along with the total caloric intake. In the United States, the per-capita daily consumption of kilocalories and grams of protein rose from 3500 kcal and 101 g protein in 1909 to 3900 kcal and 111 g protein in 2006.¹ Not coincidentally, significant weight gains and the health risks associated with obesity (e.g., heart disease, diabetes, hypertension, some forms of cancer) have been noted. The Behavioral Risk Factor Surveillance System results indicate that 33% of men and 46% of women are actively trying to lose weight in the United States.²

Many health care professionals are concerned about the rising rate of obesity in this country as well as the methods by which people are trying to battle it. Current surveys report that, of those individuals who are trying to lose weight, only 19% of women and 22% of men reported using the recommended weight-loss strategy of fewer calories and more physical activity.² Some of the more popular diets are the high-protein, low-carbohydrate diets.

High-protein diets are generally higher in total fat, saturated fat, and cholesterol. Initial weight loss associated with a high-protein, high-fat diet is caused by the induction of metabolic ketosis and fluid loss from a lack of carbohydrates. Ketosis eventually suppresses the appetite, and this ultimately leads to reduced caloric intake and weight loss.

Clifton and colleagues³ evaluated the long-term success of weight-loss maintenance among subjects after they

followed either a high-protein (34% of total energy) or high-carbohydrate (64% of total energy) diet. Subjects were on the diet for 12 weeks and then assessed 52 weeks later to evaluate results. Authors concluded that sustained weight loss was not significantly different between groups but that the group with higher protein intake did experience some beneficial weight loss results, such as abdominal fat loss and total fat mass lost. Neither group reported long-term compliance with their assigned dietary regimen.

Krieger and associates⁴ reviewed findings from 87 weight-loss studies of various macronutrient restrictions. Their conclusion was that weight-loss diets with low carbohydrate (35% to 41% total energy) and high protein intake resulted in a greater loss of fat mass. However, there was also a greater loss of lean tissue (i.e., a negative effect) in the low-carbohydrate, high-protein diet, unless protein intake exceeded 1.05 g/kg body weight.

Regardless of these findings, the American Heart Association has not changed its view regarding high-protein diets. In a statement for health care professionals from the Nutrition Committee of the Council on Nutrition, Physical Activity, and Metabolism of the American Heart Association, researchers concluded that “high-protein diets are not recommended because they restrict healthful foods that provide essential nutrients and do not provide the variety of foods needed to adequately meet nutritional needs.”⁵

1. United States Department of Agriculture, Center for Nutrition Policy and Promotion. *U.S. food supply: nutrients and other food components, per capita per day, 1909 to 2006* (website): www.ers.usda.gov/Data/FoodConsumption/NutrientAvailIndex.htm. Accessed October 10 2011.

2. Bish CL, Blanck HM, Serdula MK, et al. Diet and physical activity behaviors among Americans trying to lose weight: 2000 Behavioral Risk Factor Surveillance System. *Obes Res*. 2005;13(3):596-607.

3. Clifton PM, Keogh JB, Noakes M. Long-term effects of a high-protein weight-loss diet. *Am J Clin Nutr*. 2008;87(1):23-29.

4. Krieger JW, Sitren HS, Daniels MJ, Langkamp-Henken B. Effects of variation in protein and carbohydrate intake on body mass and composition during energy restriction: a meta-regression 1. *Am J Clin Nutr*. 2006;83(2):260-274.

5. St Jeor ST, Howard BV, Prewitt TE, et al. Dietary protein and weight reduction: a statement for healthcare professionals from the Nutrition Committee of the Council on Nutrition, Physical Activity, and Metabolism of the American Heart Association. *Circulation*. 2001; 104(15):1869-1874.

women consume approximately 152% of their protein requirement daily.

Dietary Guidelines for Americans

Americans generally eat more protein than necessary, especially in the form of meat, which carries a considerable amount of saturated fat and cholesterol. There are no benefits from consuming a diet with a high animal protein content. However, some potential health risks do exist. These risks relate to certain cancers, coronary heart disease, kidney stones, and chronic renal failure (see Chapter 21) that are associated with excess protein and saturated fat.

The *Dietary Guidelines for Americans* recommend the following with regard to protein-rich foods¹¹:

- Choose a variety of protein foods, including seafood, lean meat and poultry, eggs, beans and peas, soy products, and unsalted nuts and seeds.
- Increase the amount and variety of seafood consumed by choosing seafood in place of some meat and poultry.
- Replace protein foods that are higher in solid fats with choices that are lower in solid fats and calories and/or are sources of oils.

Table 4-3 provides a comparison of protein-rich food portions.



CLINICAL APPLICATIONS

CALCULATING DIETARY REFERENCE INTAKE FOR PROTEIN

There are two ways to calculate a person's dietary recommendation for protein.

1) Dietary Reference Intakes of Acceptable Macronutrient

Distribution Range: To calculate the protein needs of an individual who is consuming 2200 kcal/day based on the Dietary Reference Intake recommendation of 10% to 35% of total kilocalories, complete the following calculations:

- (1) $2200 \text{ kcal} \times 0.10 = 220 \text{ kcal/day}$ and
- (2) $2200 \text{ kcal} \times 0.35 = 770 \text{ kcal/day}$, thus giving a range of 220 to 770 kcal/day from protein
- (3) $220 \text{ kcal} \div 4 \text{ kcal/g} = 55$ and
- (4) $770 \text{ kcal} \div 4 \text{ kcal/g} = 192.5 \text{ g}$ of protein per day, thus giving a range of 55 to 192.5 g of protein per day

2) Recommended Dietary Allowance relative to ideal body weight:

To calculate the protein needs of a woman who is 5 feet, 4 inches tall with an ideal body weight of 120 lb (see Chapter 15) based on the Recommended Dietary Allowance of 0.8 g protein/kg body weight per day, perform the following calculations:

- (1) Convert weight in pounds to weight in kg ($2.2 \text{ lb} = 1 \text{ kg}$) as follows: $120 \text{ lb} \div 2.2 \text{ lb/kg} = 54.5 \text{ kg}$
- (2) $54.5 \text{ kg} \times 0.8 \text{ g/kg} = 43.6 \text{ g protein per day}$

Therefore, a woman who measures 5 feet, 4 inches tall and who is consuming 2200 kcal/day with a minimum of 10% of her calories coming from high-quality protein will safely obtain her Recommended Dietary Allowance for protein of 43.6 g per day.

TABLE 4-3 FOODS THAT ARE HIGH IN PROTEIN*

Food	Approximate Amount	Protein (g)
Veal, leg, meat only, braised	3 oz cooked	31.2
Beef, top round, trimmed of fat	3 oz cooked	30.7
Chicken, breast, meat only, roasted	3 oz cooked	26.7
Tuna, fresh, bluefin, cooked with dry heat	3 oz cooked	25.4
Turkey, meat only, roasted	3 oz cooked	24.9
Goose, meat only, roasted	3 oz cooked	24.6
Pork, sirloin, boneless, roasted	3 oz cooked	24.5
Halibut, fresh, cooked with dry heat	3 oz cooked	22.7
Liver, chicken, pan fried	3 oz cooked	21.9
Lamb, shoulder, trimmed to ¼-inch of fat, broiled	3 oz cooked	21.7
Tuna, canned in water, drained	3 oz cooked	21.7
Beef, ground, 70% lean, 30% fat, pan browned	3 oz cooked	21.7
Haddock, cooked with dry heat	3 oz cooked	20.6
Duck, meat only, roasted	3 oz cooked	20
Scallops, steamed	3 oz cooked	19.7
Salmon, Atlantic, cooked with dry heat	3 oz cooked	18.8
Soy burger	3 oz cooked	16.1
Oysters, cooked with moist heat	3 oz cooked	16.1
Tofu, fried	3 oz	14.6
Ham, sliced, 11% fat	3 oz cooked	14.1
Cottage cheese, 2% milk fat	3 oz	11.7
Soy milk	1 cup	11
Milk, 1% fat	1 cup	9.7
Peanut butter, smooth	2 Tbsp	8
Lentils, boiled	3 oz cooked	7.7
Kidney beans, boiled	3 oz cooked	7.4
Cheddar cheese	1 oz	7
Egg, whole, scrambled	1 large	6.8
Yogurt, plain, skim milk	3 oz	4.9

*Listed in decreasing order of protein per serving.

Data from the U.S. Department of Agriculture, Agricultural Research Service, Nutrient Data Laboratory. *Nutrient Data Laboratory home page* (website): www.ars.usda.gov/ba/bhnrc/ndl. Accessed September 22, 2011.

MyPlate

As with the other macronutrient recommendations from the MyPlate, Americans are encouraged to consume a variety of foods to meet all of their nutrient needs (see Figure 1-3).¹² The MyPlate Web site (www.choosemyplate.gov/) includes tips for choosing

lean sources of meat, poultry, and fish as well as protein alternatives such as beans, nuts, and seeds. A personalized plan can be obtained by entering an individual's age, sex, height, weight, and physical activity level. Sample menus for nonvegetarians and eating tips for vegetarian lifestyles are also available.

SUMMARY

- Protein provides the human body with amino acids, which are its primary tissue-building units. Of the 20 common amino acids, 9 are indispensable in the diet, because the body cannot manufacture them as it can the remaining 11.
- Foods that supply all of the indispensable amino acids are called *complete proteins*; these foods are mostly of animal origin. Plant protein foods are considered incomplete proteins, because they lack one or more of the indispensable amino acids. The exception is soy protein, which is of plant origin and provides complete proteins.
- Strict vegan diets involve only plant proteins, but other vegetarian diets may include dairy products, eggs, and sometimes fish. Without proper planning, only vegans risk protein imbalance and other nutritional deficiencies in iron, zinc, calcium, vitamin B₁₂, and omega-3 fatty acids.
- A constant turnover of tissue protein occurs between tissue anabolism and tissue catabolism. Adequate dietary protein and a reserve pool of amino acids help to maintain this overall protein balance. Nitrogen balance is a measure of overall protein balance.
- A mixed diet that includes a variety of foods, together with sufficient nonprotein kilocalories from the primary fuel foods (i.e., carbohydrates), supplies a balance of protein and other nutrients.
- After protein foods are eaten, a powerful digestive team of six protein-splitting enzymes frees individual amino acids for absorption.
- Protein requirements are principally influenced by growth needs and the nature of the diet in terms of protein quality and energy intake. Clinical influences on protein needs include fever, disease, surgery, and other trauma to body tissues.

CRITICAL THINKING QUESTIONS

1. What is the difference between indispensable and dispensable amino acids? Why is this difference important?
2. Compare complete and incomplete protein foods. Give examples of each.
3. Describe the different types of vegetarian diets. Compare each in terms of protein quality and risk for nutrient deficiencies. What recommendations would you offer to someone who is following a vegan diet?
4. Describe the factors that influence protein requirements.

CHAPTER CHALLENGE QUESTIONS

True-False

Write the correct statement for each statement that is false.

1. *True or False:* Complete proteins of high biologic value are found in whole grains, dried beans and peas, and nuts.
2. *True or False:* The primary function of dietary protein is to supply the necessary amino acids to build and repair body tissue.
3. *True or False:* Protein provides a main source of body heat and muscle energy.
4. *True or False:* The average American diet contains a relatively small amount of protein.
5. *True or False:* Because they are smaller, infants and young children need less protein per unit of body weight as compared with adults.
6. *True or False:* Healthy adults are in a state of nitrogen balance.
7. *True or False:* Positive nitrogen balance exists during periods of rapid growth (e.g., infancy, adolescence).
8. *True or False:* When negative nitrogen balance exists, an individual is less able to resist infection.
9. *True or False:* Egg protein has a higher biologic value than meat protein.

CHAPTER 5

Digestion, Absorption, and Metabolism

KEY CONCEPTS

- Through a balanced system of mechanical and chemical digestion, food is broken down into smaller substances, and the nutrients are then released for biologic use.
- Special organ structures and functions accomplish these tasks through the successive parts of the overall system.
- Absorption, transport, and metabolism allow for the distribution, use, and storage of nutrients throughout the body.

As described in previous chapters, nutrients that the body requires do not come ready to use; rather, they are packaged as foods in a variety of forms. Therefore, whole food must be broken down into smaller substances for absorption and metabolism to meet the body's needs. Digestion of the macronutrients—carbohydrates, fat, and protein—has been discussed in preceding chapters.

This chapter views the overall process of food digestion and nutrient absorption as one continuous whole that involves a series of successive events. In addition, metabolism and the unique body structures and functions that make this process—as well as life—possible are reviewed.

DIGESTION

Basic Principles

Principle of Change

Body cells cannot use food as it is eaten. Food must be changed into simpler substances for absorption and then into even more simple substances that cells can use to sustain life. Preparing food for the body's use involves many steps, including **digestion**, **absorption**, **transport**, and **metabolism**.

Principle of Wholeness

The different parts of the gastrointestinal (GI) tract and accessory organs are shown in Figure 5-1. The individual parts of the GI system works systematically together as a

digestion the process by which food is broken down in the gastrointestinal tract to release nutrients in forms that the body can absorb.

absorption the process by which nutrients are taken into the cells that line the gastrointestinal tract.

transport the movement of nutrients through the circulatory system from one area of the body to another.

metabolism the sum of the vast number of chemical changes in the cell that ultimately produce the materials that are essential for energy, tissue building, and metabolic controls.

Multiple Choice

- Nine of the 20 amino acids are indispensable, which means that
 - the body cannot make them and must obtain them from the diet.
 - they are required for body processes and the rest are not.
 - the body makes them because they are essential to life.
 - after making them, the body uses them for growth.
- A complete protein food of high biologic value contains
 - all 20 of the amino acids in sufficient amounts to meet human requirements.
 - the nine indispensable amino acids in any proportion, because the body can always fill in the remaining differences.
 - all of the 20 amino acids from which the body can make additional amounts of the nine indispensable ones as necessary.
 - all nine of the indispensable amino acids in correct proportion to meet human requirements.
- A state of negative nitrogen balance may occur during periods of
 - pregnancy.
 - adolescence.
 - injury or surgery.
 - infancy.

 Please refer to the Students' Resource section of this text's Evolve Web site for additional study resources.

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FURTHER READING AND RESOURCES

The following organizations are good sources of information about vegetarian diets.

Food and Nutrition Information Center. <http://fnic.nal.usda.gov>

Medline Plus (key search word: "vegetarianism"). www.nlm.nih.gov/medlineplus/vegetariandiet.html

North American Vegetarian Society. www.navs-online.org

Vegetarian Nutrition Dietetic Practice Group. www.vegetariannutrition.net

The Vegetarian Resource Group. www.vrg.org

Fuhrman J, Ferreri DM. Fueling the vegetarian (vegan) athlete. *Curr Sports Med Rep*. 2010;9(4):233-241.

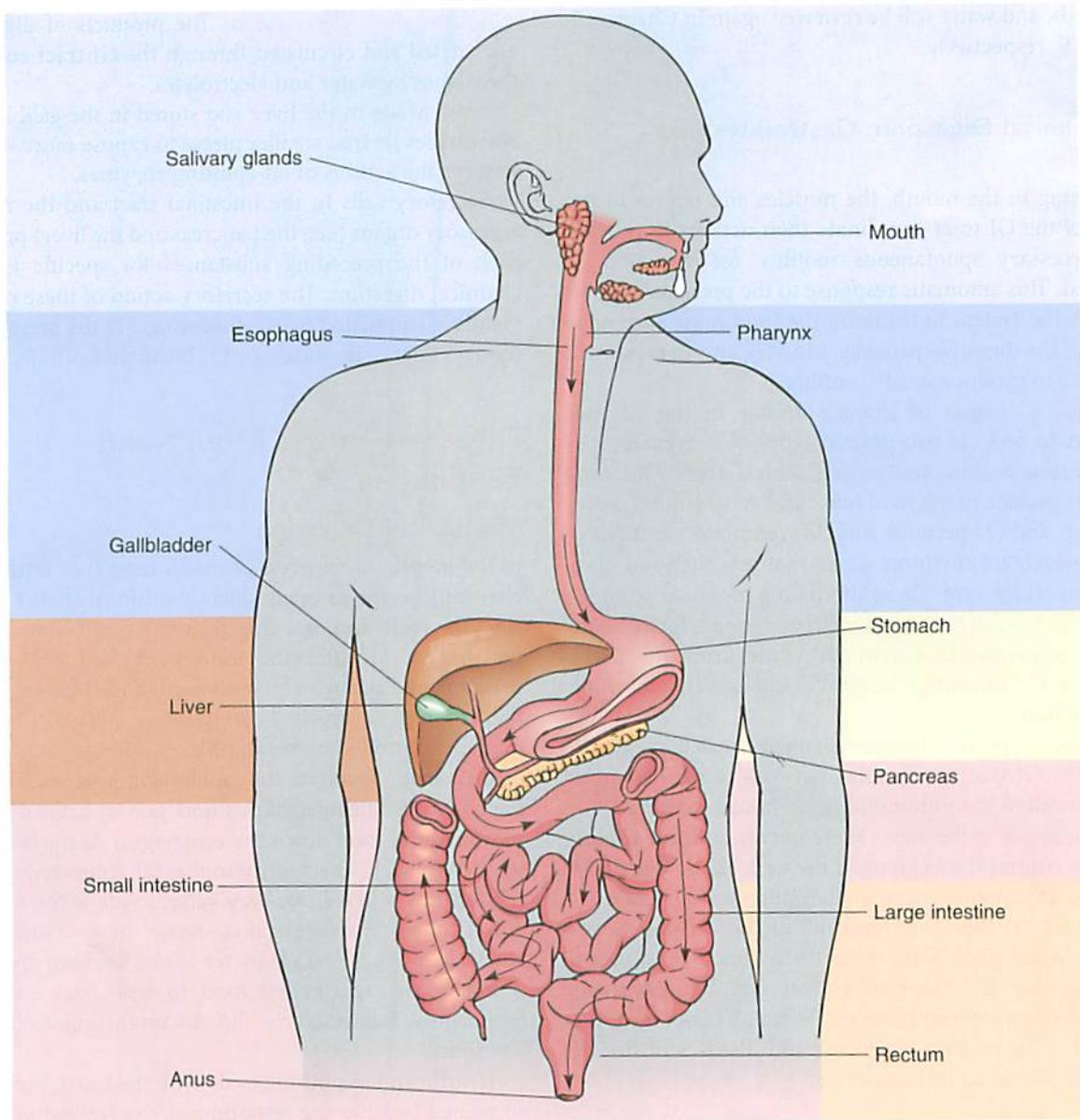


Figure 5-1 The gastrointestinal system. Through the successive parts of the system, multiple activities of digestion liberate food nutrients for use. (Courtesy Rolin Graphics.)

whole to complete the process of digestion and metabolism. Food components travel through this system until they ultimately are absorbed and delivered to the cells or excreted as waste.

Mechanical and Chemical Digestion

For nutrients to be absorbed, food must go through a series of mechanical and chemical changes. Together, these two actions encompass the overall process of digestion.

The specific mechanical and chemical actions that occur during the digestion of the macronutrients (i.e., carbohydrates, proteins, and fats) have previously been discussed. Of the micronutrients, most vitamins and minerals require little to no digestion. There are some exceptions (e.g., vitamins A and B₁₂, biotin) that require digestion before absorption can take place. Water does not require digestion, and it is easily absorbed into the general circulation. This chapter touches on those actions as a whole and as an interdependent process. Vitamins,

minerals, and water will be reviewed again in Chapters 7, 8, and 9, respectively.

Mechanical Digestion: Gastrointestinal Motility

Beginning in the mouth, the muscles and nerves in the walls of the GI tract coordinate their actions to provide the necessary spontaneous motility for digestion to proceed. This automatic response to the presence of food enables the system to break up the food mass and move it along the digestive pathway. Muscles and nerves work together to produce steady motility.

Muscles. Layers of smooth muscle in the GI wall interact to provide two general types of movement: (1) muscle tone or tonic contraction, which ensures the continuous passage of the food mass and valve control along the way; and (2) periodic muscle contraction and relaxation, which are rhythmic waves that mix the food mass and move it forward. These alternating muscular contractions and relaxations that force the contents forward are known as *peristalsis*, a term that comes from the Greek words *peri*, meaning “around,” and *stalsis*, meaning “contraction.”

Nerves. Specific nerves regulate muscular action along the GI tract. A complex network of nerves in the GI wall called the *intramural nerve plexus* extends from the esophagus to the anus. These nerves do three things: (1) they control muscle tone in the wall; (2) they regulate the rate and intensity of the alternating muscle contractions; and (3) they coordinate all of the various movements. When all is well, these finely tuned movements flow together like those of a great symphony, without conscience awareness. However, when all is not well, the discord is felt as pain. Problems and diseases of the GI tract are discussed in Chapter 18.

Chemical Digestion: Gastrointestinal Secretions

A number of secretions work together to make chemical digestion possible. Five types of substances generally are involved.

Hydrochloric Acid and Buffer Ions. Hydrochloric acid and buffer ions are needed to produce the correct pH (i.e., the degree of acidity or alkalinity) that is necessary for enzymatic activity.

Enzymes. Digestive enzymes are proteins of a specific kind and quantity for breaking down nutrients.

Mucus. Secretions of mucus lubricate and protect the mucosal tissues that line the GI tract, and they help to mix the food mass.

Water and Electrolytes. The products of digestion are carried and circulated through the GI tract and into the tissues by water and electrolytes.

Bile. Made in the liver and stored in the gallbladder, bile divides fat into smaller pieces to expose more surface area for the actions of fat-splitting enzymes.

Secretory cells in the intestinal tract and the nearby accessory organs (i.e., the pancreas and the liver) produce each of the preceding substances for specific jobs in chemical digestion. The secretory action of these cells or glands is stimulated by the following: (1) the presence of food; (2) nerve impulses; or (3) hormonal stimuli.

Digestion in the Mouth and Esophagus

Mechanical Digestion

In the mouth, the process of mastication (i.e., biting and chewing) begins to break down food into smaller particles. The teeth and oral structures are particularly suited for this work. After the food is chewed, the mixed mass of food particles is swallowed, and it passes down the esophagus, largely as a result of peristaltic waves that are controlled by nerve reflexes. Muscles at the base of the tongue facilitate the swallowing process. Then, if the body is in the upright position, gravity helps with the movement of food down the esophagus. At the entrance to the stomach, the gastroesophageal sphincter muscle relaxes, much like a one-way valve, to allow the food to enter; it then constricts again to retain the food within the stomach cavity. If the sphincter is not working properly, it may allow acid-mixed food to seep back into the esophagus. The result is the discomforting feeling of heartburn.

Heartburn has nothing to do with the heart, but it was so named because the sensations are perceived as originating in the region of the heart. A hiatal hernia is another common cause of heartburn; this occurs when part of the stomach protrudes upward into the chest cavity (i.e., the thorax; see Chapter 18).

Chemical Digestion

The salivary glands secrete material that contains **salivary amylase**, which is also called *ptyalin*. *Amylase* is the general name for any starch-splitting enzyme. Small

salivary amylase a starch-splitting enzyme in the mouth that is secreted by the salivary glands and that is commonly called *ptyalin* (from the Greek word *ptyalon*, meaning “spittle”).

glands at the back of the tongue (i.e., von Ebner's glands) secrete lingual lipase. *Lipase* is the general name for any fat-splitting enzyme. However, in this case, food does not remain in the mouth long enough for much chemical action to occur. During infancy, lingual lipase is a more relevant enzyme for the digestion of milk fat. The salivary glands also secrete a mucous material that lubricates and binds food particles to facilitate the swallowing of each food bolus (i.e., lump of food material). Mucous glands also line the esophagus, and their secretions help to move the food mass toward the stomach.

Digestion in the Stomach

Mechanical Digestion

Under sphincter-muscle control from the esophagus, which joins the stomach at the cardiac notch, the food enters the fundus (i.e., the upper portion of the stomach) in individual bolus lumps. Within the stomach, muscles gradually knead, store, mix, and propel the food mass forward in slow, controlled movements. By the time the food mass reaches the antrum (i.e., the lower portion of the stomach), it is now a semiliquid, acid-food mix called *chyme*. A constricting sphincter muscle at the end of the stomach called the *pyloric valve* controls the flow at this point. This valve slowly releases acidic chyme so that it can be quickly buffered by the alkaline intestinal secretions and not irritate the mucosal lining of the duodenum, which is the first section of the small intestine. The caloric density of a meal, which mainly results from its fat composition, influences the rate of stomach emptying at the pyloric valve. The major parts of the stomach are shown in Figure 5-2.

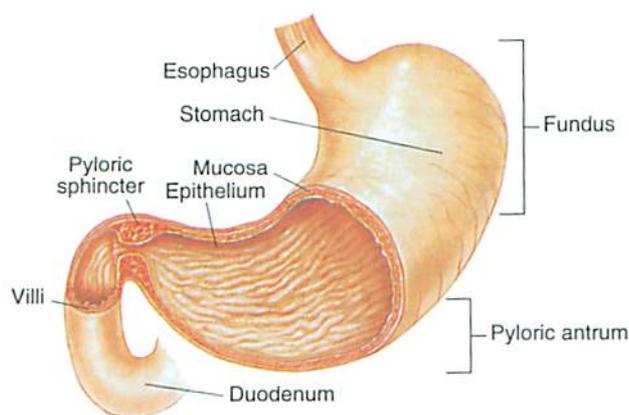


Figure 5-2 Stomach. (Reprinted from Raven PH, Johnson GB. *Biology*, 3rd ed. New York: McGraw-Hill; 1992.)

Chemical Digestion

The gastric secretions contain three types of materials that help with chemical digestion in the stomach.

Acid. The hormone *gastrin* stimulates parietal cells within the lining of the stomach to secrete hydrochloric acid. Hydrochloric acid creates the necessary degree of acidity for gastric enzymes to work, and it also activates the first protease, pepsinogen, in the stomach.

Mucus. Mucous secretions protect the stomach lining from the erosive effect of hydrochloric acid. Secretions also bind and mix the food mass and help to move it along.

Enzymes. The inactive enzyme pepsinogen is secreted by stomach cells, and it is activated by hydrochloric acid to become the protein-splitting enzyme *pepsin*. Other cells produce small amounts of a specific gastric lipase called *tributyrylase*, which works on tributyrin (i.e., butterfat); however, this is a relatively minor activity in the stomach.

Various sensations, emotions, and foods stimulate the nerve impulses that trigger these secretions. The concept that the stomach is said to “mirror the person within” is not without merit. For example, anger and hostility increase secretions, whereas fear and depression decrease secretions and inhibit blood flow and motility. Additional hormonal stimulus occurs in response to food entering the stomach.

Digestion in the Small Intestine

Up to this point, the digestion of food has largely been mechanical, and it has resulted in the delivery of a semifluid mixture of fine food particles and watery secretions to the small intestine. Chemical digestion has been minimal. Thus, the major task of digestion and the absorption that follows occurs in the small intestine. The structural parts, synchronized movements, and array of specific enzymes of the small intestine are highly developed for the final step of mechanical and chemical digestion.

chyme the semifluid food mass in the gastrointestinal tract that is present after gastric digestion.

gastrin a hormone that helps with gastric motility, that stimulates the secretion of gastric acid by the parietal cells of the stomach, and that stimulates the chief cells to secrete pepsinogen.

pepsin the main gastric enzyme specific to proteins; it begins breaking large protein molecules into shorter-chain polypeptides; gastric hydrochloric acid is necessary for its activation.

Mechanical Digestion

Under the control of nerve impulses, the muscular walls of the small intestines stretch from the food mass or hormonal stimuli, and the intestinal muscles produce several types of movement that aid digestion, as follows:

- *Peristaltic waves* slowly push the food mass forward, sometimes with long, sweeping waves over the entire length of the intestine.
- *Pendular movements* from small, local muscles sweep back and forth, thereby stirring the chyme at the mucosal surface.
- *Segmentation rings* from the alternating contraction and relaxation of circular muscles progressively chop the food mass into successive soft lumps and then mix them with secretions.
- *Longitudinal rotation* by long muscles that run the length of the intestine rolls the slowly moving food mass in a spiral motion to mix it and expose new surfaces for absorption.
- *Surface villi motions* stir and mix the chyme at the intestinal wall, thereby exposing additional nutrients for absorption.

Chemical Digestion

The small intestines, together with the GI accessory organs (i.e., the pancreas, liver, and gallbladder), supply many secretory materials to accomplish the major chore of chemical digestion. The pancreas and intestines secrete enzymes that are specific for the digestion of each macronutrient.

Pancreatic Enzymes

1. **Carbohydrate:** **Pancreatic amylase** converts starch into the disaccharides maltose, and sucrose.
2. **Protein:** **Trypsin** and **chymotrypsin** split large protein molecules into smaller and smaller peptide fragments and finally into single amino acids. **Carboxypeptidase** removes end amino acids from peptide chains.
3. **Fat:** **Pancreatic lipase** converts fat into glycerides and fatty acids.

Intestinal Enzymes

1. **Carbohydrate:** Disaccharidases (i.e., maltase, lactase, and sucrase) convert their respective disaccharides (i.e., maltose, lactose, and sucrose) into monosaccharides (i.e., glucose, galactose, and fructose).
2. **Protein:** The intestinal enzyme enterokinase activates trypsinogen, which is released from the pancreas to become the protein-splitting enzyme trypsin. Amino peptidase removes end amino acids from polypeptides. Dipeptidase splits dipeptides into their two remaining amino acids.
3. **Fat:** Intestinal lipase splits fat into glycerides and fatty acids.

Mucus. Large quantities of mucus, which are secreted by intestinal glands, protect the mucosal lining from the irritation and erosion caused by the highly acidic gastric contents that enter the duodenum.

Bile. Bile is an emulsifying agent and an important part of fat digestion and absorption. It is produced by the liver and stored in the adjacent gallbladder, and it is ready for use when fat enters the intestine.

Hormones. The hormone secretin, which is produced by the mucosal glands in the first part of the intestine, controls the acidity and secretion of enzymes from the pancreas. The resulting alkaline environment in the small intestine, with a pH greater than 8, is necessary for the activity of the pancreatic enzymes. The hormone cholecystokinin, which is secreted by intestinal mucosal glands when fat is present, triggers the release of bile from the gallbladder to emulsify fat.

The arrangement of accessory organs to the duodenum, which is the first section of the small intestine, is shown in Figure 5-3. These organs make up the biliary system. The liver is sometimes called the “metabolic capital” of the body, because it performs numerous functions for the metabolism of all converging nutrients (Box 5-1). The liver’s many metabolic functions are reviewed in greater detail in Chapter 18.

The various nerve and hormone controls of digestion are illustrated in Figure 5-4. Although small individual summaries of digestion are given in each of the macronutrient chapters, a general summary of the entire digestive process is shown in Figure 5-5 so that the overall process can be viewed as it is: one continuous and integrated whole.

pancreatic amylase a major starch-splitting enzyme that is secreted by the pancreas and that acts in the small intestine.

trypsin a protein-splitting enzyme produced in the pancreas and released into the small intestine; the inactive precursor trypsinogen is activated by enterokinase.

chymotrypsin one of the protein-splitting and milk-curdling pancreatic enzymes that is activated in the small intestine from the precursor chymotrypsinogen; it breaks specific amino acid peptide links of protein.

carboxypeptidase a protein enzyme that splits off the carboxyl group (i.e., $-\text{COOH}$) at the end of peptide chains.

pancreatic lipase a major fat-splitting enzyme produced by the pancreas and secreted into the small intestine to digest fat.

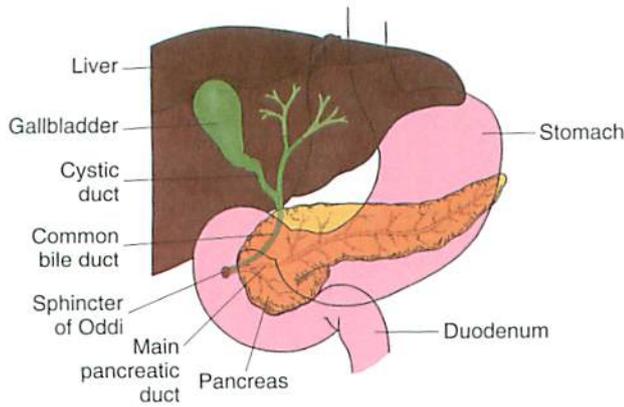


Figure 5-3 Organs of the biliary system and the pancreatic ducts.

ABSORPTION AND TRANSPORT

When digestion is complete, food has been changed into simple end products that are ready for cell use. Carbohydrate foods are reduced to the simple sugars glucose, fructose, and galactose, and fats are transformed into fatty acids and glycerides. Protein foods are changed into single amino acids, and vitamins and minerals are also liberated. With a water base for solution and transport in addition to the necessary electrolytes, the whole fluid food-derived mass is now prepared for absorption. For many nutrients, especially certain vitamins and minerals, the point of absorption becomes the vital gatekeeper that determines how much of a given nutrient is kept for body use. Although the GI tract is quite efficient, 100% of all

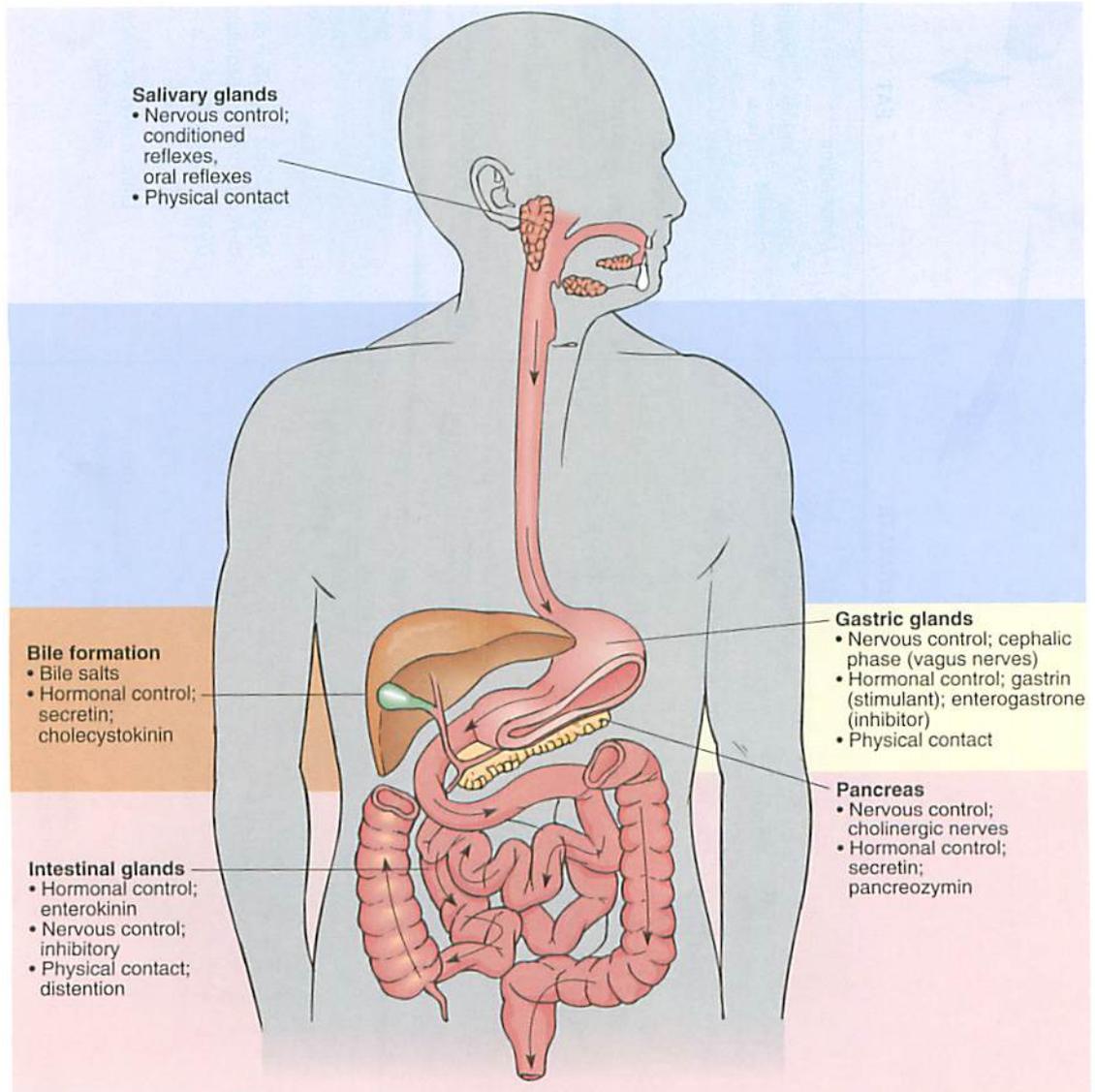


Figure 5-4 Summary of the factors that influence secretions in the gastrointestinal tract. (Courtesy Rolin Graphics.)

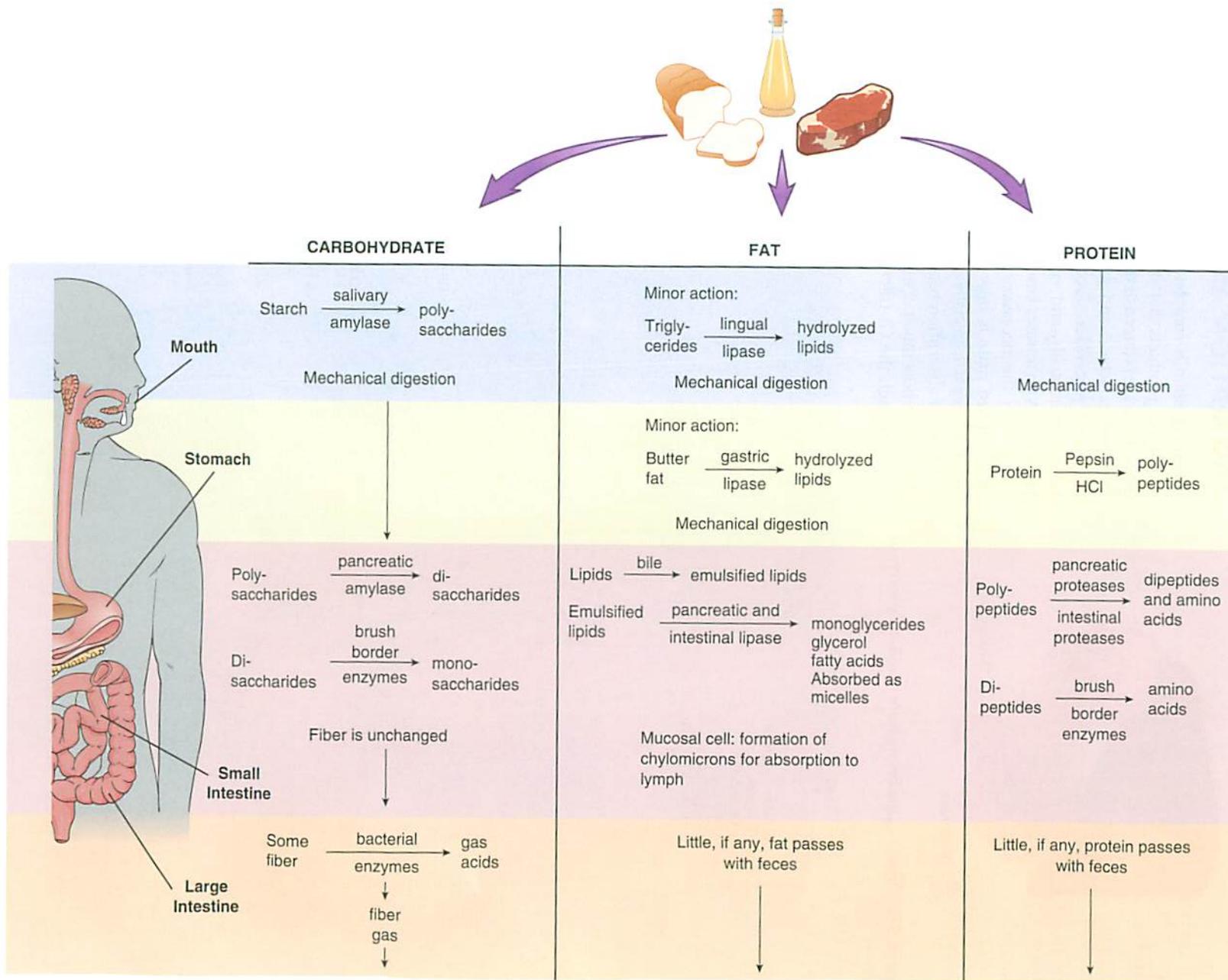


Figure 5-5 Summary of the digestive processes. (Courtesy Rolin Graphics.)

BOX 5-1 FUNCTIONS OF THE LIVER**Major Functions**

- Bile production
- Synthesis of proteins and blood-clotting factors
- Metabolism of hormones and medications
- Regulation of blood glucose levels
- Urea production to remove the waste products of normal metabolism

Specific Metabolic Functions of the Macronutrients

- Lipolysis: breaking down lipids into fatty acids and glycerol
- Lipogenesis: building up lipids from fatty acids and glycerol
- Glycolysis: breaking down glucose into pyruvate to enter the Krebs cycle
- Gluconeogenesis: converting noncarbohydrate substances into glucose
- Glycogenolysis: breaking down glycogen into individual glucose units
- Glycogenesis: combining units of glucose to store as glycogen
- Protein degradation: breaking down proteins into single amino acids
- Protein synthesis: building complete proteins from individual amino acids

nutrients consumed is not absorbed as a result of varying degrees of bioavailability. A nutrient's bioavailability depends on the following: (1) the amount of nutrient present in the GI tract; (2) competition among nutrients for common absorptive sites; and (3) the form in which the nutrient is present. This degree of bioavailability is a factor in setting dietary intake standards for all macronutrients and micronutrients.¹⁻⁶

Absorption in the Small Intestine**Absorbing Structures**

Three important structures of the intestinal wall surface (Figure 5-6) are particularly adapted to ensure the maximal absorption of essential nutrients in the digestive process:

- **Mucosal folds:** Like the hills and valleys of a mountain range, the surface of the small intestine piles into many folds. **Mucosal folds** can easily be seen when such tissue is examined.
- **Villi:** Closer examination under a regular light microscope reveals small, finger-like projections that cover the piled-up folds of the mucosal lining. These little **villi** further increase the area of exposed surface. Each villus has an ample supply of blood vessels to receive protein and carbohydrate materials as well as a lymph vessel to receive

fat-soluble nutrients. This lymph vessel is called a *lacteal*, because the fatty chyme is creamy at this point and looks like milk.

- **Microvilli:** Even closer examination with an electron microscope reveals a covering of smaller projections on the surface of each tiny villus. The covering of **microvilli** on each villus is called the *brush border*, because it looks like bristles on a brush.

These three unique structures of the inner intestinal wall—folds, villi, and microvilli—combine to make the inner surface some 600 times greater than the area of the outer surface of the intestine. The length of the small intestine is approximately 660 cm (22 ft). This remarkable organ is well adapted to deliver nutrients into the circulation to the body's cells. If its entire surface were spread out on a flat plane, the total surface area is estimated to be as large as half of a basketball court. Far from being the lowly gut, the small intestine is one of the most highly developed, exquisitely fashioned, and specialized tissues in the body.

Absorption Processes

A number of absorbing processes complete the task of moving vital nutrients across the inner intestinal wall and into the body circulation (Figure 5-7). These processes include diffusion, energy-driven active transport, and pinocytosis:

- **Simple diffusion** is the force by which particles move outward in all directions from an area of greater concentration to an area of lesser concentration. Small materials that do not need the help of a specific protein channel to move across the mucosal cell wall use this method.
- **Facilitated diffusion** is similar to simple diffusion, but it makes use of a protein channel for the carrier-assisted movement of larger items across the mucosal cell membrane.

mucosal folds the large, visible folds of the mucous lining of the small intestine that increase the absorbing surface area.

villi small protrusions from the surface of a membrane; finger-like projections that cover the mucosal surfaces of the small intestine and that further increase the absorbing surface area; they are visible through a regular microscope.

microvilli extremely small, hair-like projections that cover all of the villi on the surface of the small intestine and that greatly extend the total absorbing surface area; they are visible through an electron microscope.

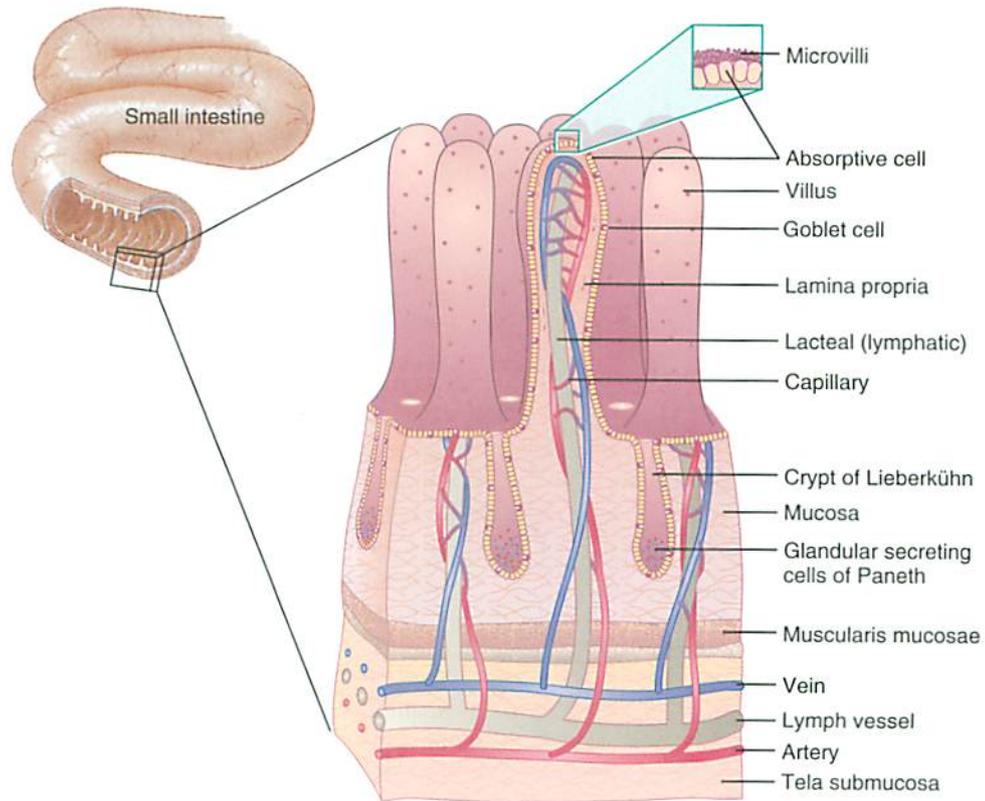


Figure 5-6 The intestinal wall. A diagram of the villi of the human intestine that shows its structure and the blood and lymph vessels. (Reprinted from Mahan LK, Escott-Stump S. *Krause's food & nutrition therapy*. 12th ed. Philadelphia: Saunders; 2008.)

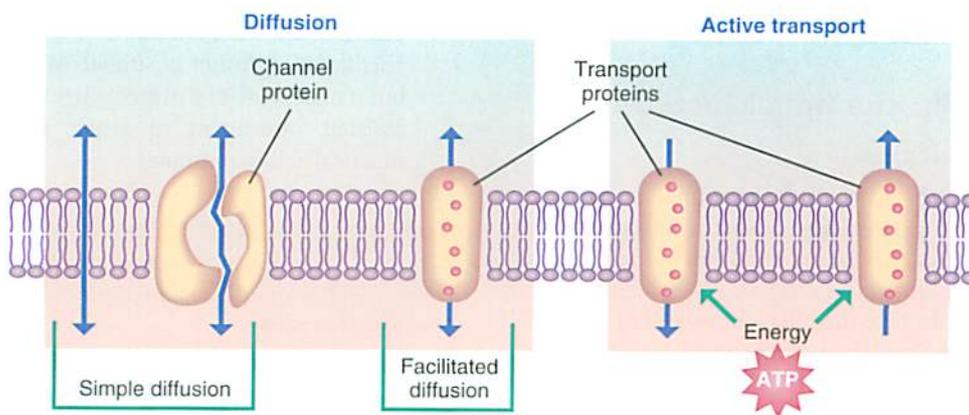


Figure 5-7 Transport pathways through the cell membrane. (Reprinted from Mahan LK, Escott-Stump S. *Krause's food & nutrition therapy*. 12th ed. Philadelphia: Saunders; 2008.)

- *Active transport* is the force by which particles move against their concentration gradient. Active transport mechanisms usually require some sort of carrier partner to help ferry the particles across the membrane. For example, glucose enters absorbing cells through an active transport mechanism that involves sodium as a partner.
- *Pinocytosis* is the penetration of larger materials by attaching to the thicker cell membrane and being engulfed by the cell.

Absorption in the Large Intestine

Water

The main absorptive task that remains for the large intestine is to absorb water. Most water in the chyme that enters the large intestine is absorbed in the first half of the colon. Only a small amount (approximately 100 mL) remains to form the feces and be eliminated.

Dietary Fiber

Food fiber is not digested, because humans lack the specific enzymes that are required to break the beta bonds between molecules. However, dietary fiber contributes important bulk to food mass and helps to form feces. The formation and passage of intestinal gas is a normal process of healthy digestion, but it can be problematic for some individuals (see the Clinical Applications box, “The Sometimes Embarrassing Effects of Digestion”).

Macronutrients and Micronutrients

Table 5-1 summarizes the major features of intestinal nutrient absorption, including macronutrients and micronutrients. In addition, Figure 5-8 shows the location of absorption of each nutrient as well as the route through which it is absorbed (i.e., lymph or blood).

Transport

After being broken down from food and absorbed, nutrients must be transported to various cells throughout the body. This transportation requires the work of both the vascular and lymphatic systems (see Figure 5-6).

Vascular System

The vascular system is composed of veins and arteries, and it is responsible for supplying the entire body with nutrients, oxygen, and many other vital substances that are necessary for life via the blood. In addition, the vascular system transports waste (e.g., carbon dioxide, nitrogen) to the lungs and kidneys for removal.

Most of the products of digestion are water-soluble nutrients, which therefore can be absorbed into the vascular system (i.e., the blood circulatory system) directly from the intestinal cells. The nutrients travel first to the liver for immediate cell enzyme work before being dispersed to other cells throughout the body. The portion of circulation from the intestines to the liver is called the *portal circulation*.

Lymphatic System

Because fatty materials are not water soluble, another route must be provided. These fat molecules pass into the lymph vessels in the villi (e.g., the lacteals), flow into the larger lymph vessels of the body, and eventually enter the bloodstream through the thoracic duct.

Metabolism

At this point, the individual macronutrients in food have been broken down through digestion into the basic building blocks (i.e., monosaccharides, amino acids, and fatty acids) and absorbed into the bloodstream or the lymphatic system. Now these nutrients can be converted into needed energy or stored in the body for later use.

In addition, the micronutrients (i.e., vitamins and minerals) have been liberated from any bound proteins, and they are free for absorption. Once inside, the micronutrients are dispersed throughout the body for their many critical functions.

Energy for Fuel

Metabolism is the sum of the chemical reactions that occur within a living cell to maintain life. The mitochondrion of the cell is the work center in which all metabolic reactions take place. The two types of metabolism are **catabolism** and **anabolism**. Catabolism is the breaking down of large substances into smaller units. For example, breaking down stored glycogen into its smaller building blocks (i.e., glucose) is a catabolic reaction. Anabolism is the opposite; it is the process by which cells build large substances from smaller particles, such as building a complex protein from single amino acids.

catabolism the metabolic process of breaking down large substances to yield smaller building blocks.

anabolism the metabolic process of building large substances from smaller parts; the opposite of catabolism.



CLINICAL APPLICATIONS

THE SOMETIMES EMBARRASSING EFFECTS OF DIGESTION

After eating certain foods, some people complain of the discomfort or embarrassment of gas. Gas is a normal by-product of digestion, but when it becomes painful or apparent to others, it may become a physical and social dilemma.

The gastrointestinal tract normally holds approximately 3 oz of gas that moves along with the food mass and is silently absorbed into the bloodstream. Sometimes extra gas collects in the stomach or intestine, thereby creating an embarrassing—although usually harmless—situation.

Stomach Gas

Gas in the stomach results from trapped air bubbles. It occurs when a person eats too fast, drinks through a straw, or otherwise takes in extra air while eating. Burping releases some gas, but the following tips may help to avoid uncomfortable situations:

- Avoid carbonated beverages.
- Do not gulp.
- Chew with the mouth closed.
- Do not drink from a can or through a straw.
- Do not eat while overly nervous.

Intestinal Gas

The passing of gas from the intestine can be a social embarrassment. This gas forms in the colon, where bacteria attack undigested items and cause them to decompose and produce gas. Carbohydrates release hydrogen, carbon dioxide, and—in some people with certain types of bacteria in the gut—methane. All three products are odorless (although noisy) gases. Protein produces hydrogen sulfide and volatile compounds such as indole and skatole, which add a distinctive aroma to the expelled air. The following suggestions may help to control flatulence:

- Cut down on simple carbohydrates (e.g., sugars). Especially observe milk's effect, because lactose intolerance may be the culprit. Substitute cultured forms, such as yogurt or milk treated with a lactase product such as Lactaid (McNeil Nutritionals, Fort Washington, Pa).
- Use a prior leaching process before cooking dry beans to remove indigestible saccharides such as raffinose and stachyose. Although humans cannot digest these substances, they provide a feast for bacteria in the intestines. This simple procedure eliminates a major portion of these gas-forming saccharides. First, put washed, dry beans into a large pot, add 4 cups of water for each pound of beans (approximately 2 cups), and boil the beans uncovered for 2 minutes. Remove the pot from the heat, cover it, and let it stand for 1 hour. Finally, drain and rinse the beans, add 8 cups of fresh water, bring the water to a boil, reduce the heat, and simmer the beans in a covered pot for 1 to 2 hours or until beans are tender. Season as desired.
- Eliminate known food offenders. These vary from person to person, but some of the most common offenders are beans (if they are not prepared for cooking as described), onions, cabbage, and high-fiber wheat products.

When relief has been achieved, slowly add more complex carbohydrates and high-fiber foods back into the diet. After small amounts are tolerated, try moderate increases. If no relief occurs, medical help may be needed to rule out or treat an overactive gastrointestinal tract.

The Krebs cycle, which is also known as the *citric acid cycle* or the *TCA cycle*, is the hub of energy production that occurs in the mitochondria of the cell. The combined processes of metabolism (i.e., catabolic and anabolic reactions) ensure that the body has much needed energy in the form of adenosine triphosphate (ATP). The rate of ATP production fluctuates, and it speeds up or slows down depending on energy needs at a given time. Energy needs are minimal during sleep, but they increase dramatically during strenuous physical activity. Energy supply and demand are discussed further in Chapter 6. Figure 5-9 (on page 77) illustrates a brief breakdown of the macronutrients and how they enter the final step of energy production to ultimately supply cells with ATP.

Because carbohydrates have 4 kcal/g and fat has 9 kcal/g, the metabolism of glucose yields less energy (i.e., ATP) than the metabolism of fat, gram for gram. However, the body prefers to use glucose as its primary source of energy. Protein can be used as a source of energy as well, but this is a relatively inefficient method of producing energy, and it results in extra nitrogen waste. The body only breaks down protein for energy when glucose and fatty acids are in short supply.

Stored Energy

If the amount of food consumed yields more energy than is needed to maintain voluntary and involuntary actions,

TABLE 5-1 **INTESTINAL ABSORPTION OF SOME MAJOR NUTRIENTS**

Nutrient	Form	Means of Absorption	Control Agent or Required Cofactor	Route
Carbohydrate	Monosaccharides (glucose or galactose)	Competitive Selective	—	Blood
	Fructose	Active transport by sodium pump	Sodium	
Protein	Amino acids	Facilitated diffusion	Protein carrier	Blood
	Some dipeptides	Selective	—	Blood
		Facilitated diffusion	Pyridoxine (pyridoxal phosphate)	Blood
Fat	Whole protein (rare)	Pinocytosis	Protein carrier	Blood
	Fatty acids	Fatty acid–bile complex	Bile	Lymph
	Glycerides (monoglycerides and diglycerides)	(micelles)		
	Few triglycerides (neutral fat)	Pinocytosis	—	Lymph
Vitamins	B ₁₂	Facilitated diffusion	Intrinsic factor	Blood
	A, D, E, and K	Bile complex (micelles)	Bile	Blood
Minerals	Sodium	Active transport by sodium pump	—	From the large intestine to the blood
	Calcium	Active transport	Vitamin D	Blood
	Iron	Active transport	Ferritin mechanism	Blood (as transferrin)
Water	Water	Osmosis	—	Blood, lymph, and interstitial fluid

the remaining energy is stored for later use in the body. The human body is a highly efficient organism. Energy or kilocalories in excess of needs are not wasted. Excess glucose can easily be stored as glycogen in the liver and muscles for quick energy at a later time. The anabolic process of converting extra glucose into glycogen is called *glycogenesis*.

When the glycogen reserves are full, additional excess energy from carbohydrates, fat, or protein are stored as fat in adipose tissue. *Lipogenesis* is the building up of triglycerides for storage in the *adipose tissue* of the body. Both glycogen and stored fat are available for use when energy demands require it. Energy balance and the factors that influence it are discussed further in Chapter 6.

Excess protein intake is not stored as muscle. The body uses amino acids to build functional and structural proteins as needed, and the liver stores some free amino acids to meet rapid needs of the body. However, protein intake above and beyond the body's requirements is broken down further so that the nitrogen unit is removed, and the remaining carbon chain can be converted to glucose or fat for storage. The conversion of amino acids to glucose is referred to as *gluconeogenesis*.

Although alcohol is not a nutrient, it does provide 7 kcal/g. Therefore, alcohol intake adds to the overall supply of energy (see the For Further Focus box, "What About Alcohol?").

ERRORS IN DIGESTION AND METABOLISM

The Genetic Defect

Certain food intolerances stem from underlying genetic disease. For each genetic disease, the necessary enzyme that controls the cell's metabolism of a specific nutrient

glycogenesis the anabolic process of creating stored glycogen from glucose.

lipogenesis the anabolic process of forming fat.

adipose tissue the storage site for excess fat.

gluconeogenesis the formation of glucose from non-carbohydrate substances such as amino acids.

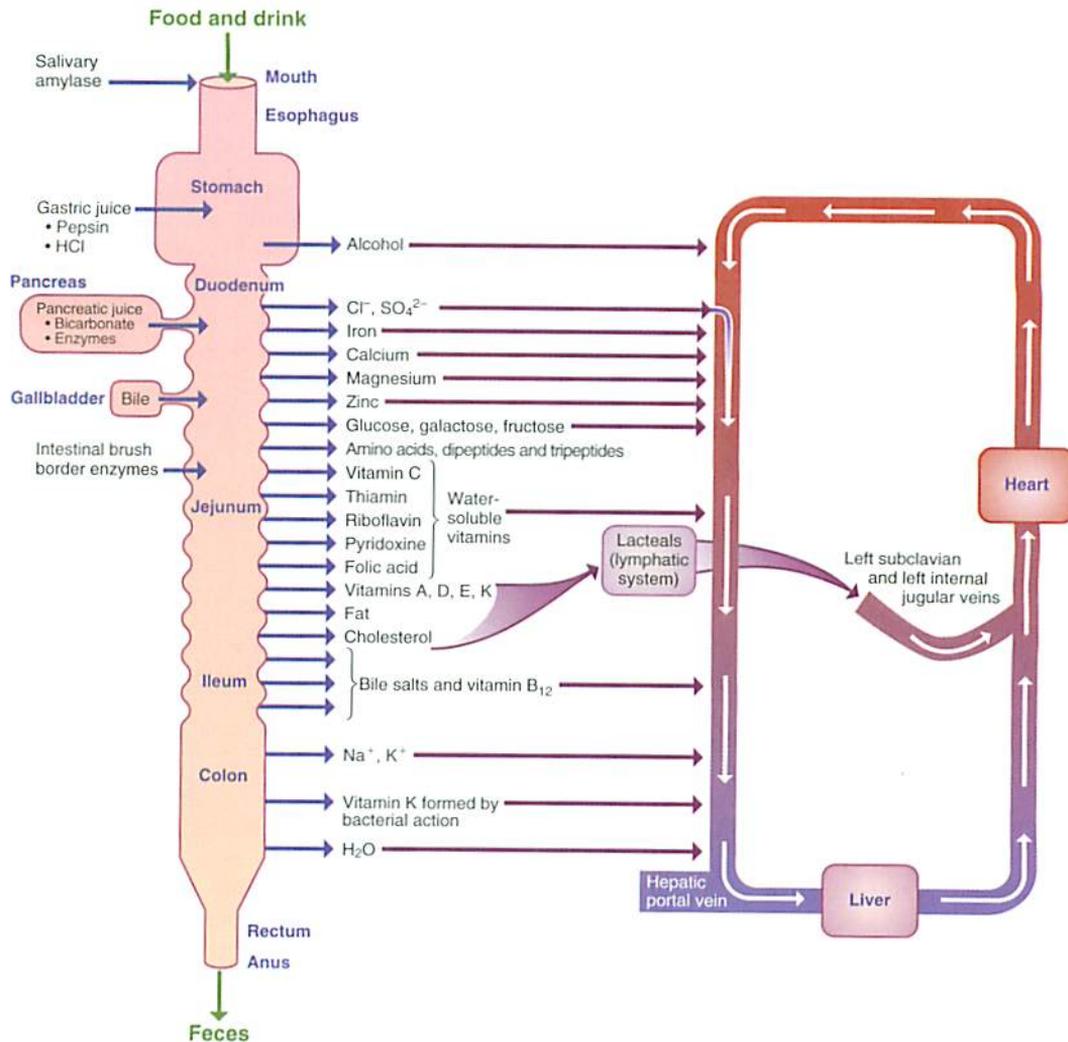


Figure 5-8 Sites of secretion and absorption in the gastrointestinal tract. (Mahan LK, Escott-Stump S. *Krause's food & nutrition therapy*. 12th ed. Philadelphia: Saunders; 2008.)

is missing, thereby preventing the normal nutrient metabolism. Three examples of genetic defects are phenylketonuria (PKU), galactosemia, and glycogen storage disease.

Phenylketonuria

PKU is an autosomal recessive genetic disorder that results when phenylalanine hydroxylase, which is the enzyme that is responsible for metabolizing the essential amino acid phenylalanine, is not produced by the body. If left untreated, this condition causes permanent mental retardation and central nervous system damage. Other possible symptoms and side effects include irritability, hyperactivity, convulsive seizures, and psychiatric disorders. PKU affects approximately 1 in every 10,000 to 15,000 live births in the United States. Screening tests

began during the 1960s, and they are now mandatory at birth in all areas of the United States. A simple blood test can identify affected infants, and thus, treatment can start immediately. With proper treatment, children with PKU grow normally and have healthy lives. The treatment is a low-phenylalanine diet of special formulas and low-protein food products for life. Unfortunately, the prescribed diet is somewhat unpalatable, and lifelong adherence is low. Intensive family counseling by a metabolic team is needed. Research into cell-directed therapy and more permanent treatments is ongoing.⁷

Galactosemia

Galactosemia is a genetic disease that affects carbohydrate metabolism and that also results from a missing enzyme. Similar to PKU, galactosemia is an autosomal recessive

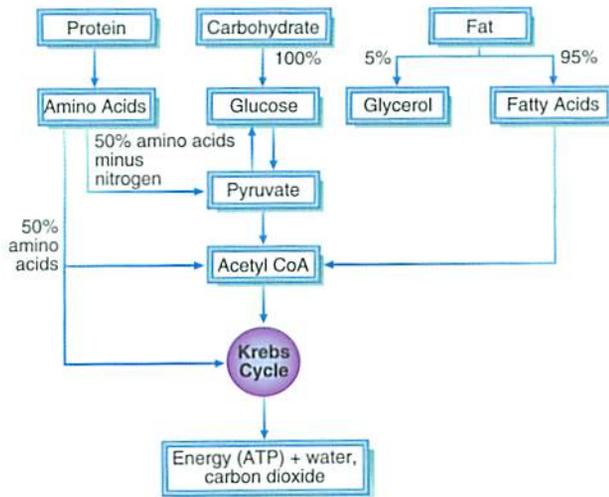


Figure 5-9 Metabolic pathways. (Reprinted from Peckenpaugh NJ. *Nutrition essentials and diet therapy*. 10th ed. Philadelphia: Saunders; 2007.)

disorder; it affects 1 in every 10,000 to 30,000 live births. The missing enzyme, galactose-1-phosphate uridylyltransferase, is one that converts galactose to glucose. Because galactose comes from the breakdown of lactose (milk sugar), all sources of lactose in the diet must be eliminated. When it is not treated, galactosemia causes brain and liver damage. Newborn screening programs, which are required in all states, identify affected infants.⁸ If treatment begins immediately, life-threatening damage may be avoided and thus, enable the child to grow normally. Treatment is a galactose-free diet, with special formulas for infants and lactose-free food guides. The treatment diet must be followed for life.

Glycogen Storage Diseases

Glycogen storage diseases (GSDs) are a group of rare genetic defects that inhibit the normal metabolic pathways of glycogen. This disease occurs in 1 of every 20,000 to 40,000 live births in the United States.⁹ Twelve distinct forms of GSD result from the absence of the enzymes that are required for the synthesis or breakdown of glycogen. The specific form of GSD is distinguished by the enzyme

FOR FURTHER FOCUS

WHAT ABOUT ALCOHOL?

Does Alcohol Provide Energy?

Yes. Alcohol contributes to the overall energy intake in the form of calories. Alcohol yields 7 kcal/g consumed. This is more than both carbohydrates and protein, which yield 4 kcal/g each.

Is Alcohol a Nutrient?

No. Unlike carbohydrates, fats, proteins, vitamins, minerals, and water, alcohol performs no essential function in the body. Alcohol is not stored in the body, but the by-products of metabolism can accumulate to toxic amounts when alcohol is consumed in large quantities.

How Is Alcohol Digested?

The majority (i.e., 85% to 95%) of alcohol is absorbed without any chemical digestion. Alcohol is one of the few substances that can be absorbed directly into the circulation from the stomach. Small amounts of alcohol can enter the blood circulation from the mouth and the esophagus. What is not absorbed in the stomach is absorbed in the small intestine and sent directly to the liver for metabolism.

How Is Alcohol Metabolized?

Alcohol metabolism takes precedence over the metabolism of any other nutrient in the body because it is a toxin. The primary by-product of alcohol metabolism is acetaldehyde, which is the culprit for the destruction of healthy tissue that

is associated with alcoholism. After detoxifying the alcohol, the liver uses remaining by-products to produce fatty acids. Fatty acids are combined with glycerol through lipogenesis to form triglycerides, and they are stored in the liver. A single drinking binge can result in an accumulation of fat in the liver. Repeated episodes over time can lead to fatty liver disease, which is the first stage of alcoholic liver disease.

Alcohol metabolism is a priority for the liver. Blood alcohol concentrations peak at approximately 30 to 45 minutes after one drink, which is defined as 12 oz of beer, 5 oz of wine, or 1.5 oz of 80-proof distilled spirits. The liver can only work so fast to metabolize and rid the body of alcohol, regardless of how much has been consumed. When consumption exceeds the rate of metabolism, alcohol and its metabolites begin to accumulate in the blood.

Several factors influence an individual's ability to metabolize alcohol, including gender, food intake, body weight, sex hormones, and medications.

More Information

To find out more about alcohol and its dangers, benefits, and associated diseases, refer to the following Web sites:

- Alcoholics Anonymous: www.aa.org
- The National Council on Alcoholism and Drug Dependence: www.ncadd.org
- National Institute on Alcohol Abuse and Alcoholism: www.niaaa.nih.gov

that is missing and the tissue affected. The liver is the primary site of glycogen metabolism; therefore, hepatic forms of GSD (e.g., von Gierke's disease or type I glycogenosis) affect the glucose availability of the whole body. Myopathic forms of GSD inhibit normal glycogen metabolism in the striated muscles, and they are less severe than hepatic forms. An example of a myopathic form is McArdle's disease (i.e., type V glycogenosis).

Other Intolerances or Allergies

Not all intolerances are genetic inborn errors of metabolism. Some problems with digestion and metabolism are the result of food intolerances or allergies. An example of a food intolerance that is caused by the inability to complete digestion is lactose intolerance.

Lactose Intolerance

A deficiency of any one of the disaccharidases (i.e., lactase, sucrase, or maltase) in the small intestine may produce a

wide range of GI problems and abdominal pain because the specific sugar involved cannot be digested (see Chapter 2). Lactose intolerance is the most common, and it presents as varying degrees of intolerance. With this condition, there is insufficient lactase to break down the milk sugar lactose; thus, lactose accumulates in the intestine, causing abdominal cramping and diarrhea. Milk and all products containing lactose are carefully avoided. Milk that is treated with a commercial lactase product and soy milk products are safe substitutes.

Allergies

This chapter is limited to digestion, metabolism, transport, and absorption; therefore, allergic reactions (e.g., celiac disease) are not covered here. Allergies are inappropriate immune responses to substances that are not otherwise harmful and not necessarily problems with digestion or metabolism. Issues that are specific to GI disorders and allergies are covered in more detail in Chapter 18.

SUMMARY

- Necessary nutrients as they occur in food are not usable by the human body; they must be changed, released, regrouped, and rerouted into forms that body cells can use. The closely related activities of digestion, absorption, and transport ensure that key food nutrients are delivered to the cells so that the multiple metabolic tasks that sustain life can be completed.
- Mechanical digestion consists of spontaneous muscular activity that is responsible for the initial mechanical breakdown by mastication and the movement of the food mass along the GI tract by motions such as peristalsis.
- Chemical digestion involves enzymatic action that breaks food down into progressively smaller components and then releases its nutrients for absorption.
- Absorption involves the passage of nutrients from the intestines into the mucosal lining of the intestinal wall. It primarily occurs in the small intestine as a result of the work of highly efficient intestinal wall structures that, together with a number of effective absorbing mechanisms, increase the absorbent surface area. Nutrients that are absorbed are then transported throughout the body by the blood circulation.
- The nutrients that we eat are converted into ATP through the cycles of metabolism. Metabolism is the sum of the body processes that change food energy from the macronutrients into various forms of energy. Metabolism is a balance of both anabolic and catabolic reactions.
- Genetic diseases of metabolism result from missing enzymes that control the metabolism of specific nutrients. Special diets in each case limit or eliminate the particular nutrient involved.

CRITICAL THINKING QUESTIONS

1. Describe the types of muscle movement that are involved in mechanical digestion. What does the word *motility* mean?
2. Identify the digestive enzymes and any related substances secreted by the salivary and mucosal glands, the pancreas, and the liver. What activities do they perform on carbohydrates, proteins, and fats? What stimulates the release of these enzymes?
3. Describe four mechanisms of nutrient absorption from the small intestine. Describe the routes taken by the breakdown products of carbohydrates, proteins, and fats after absorption. Why must an alternate route to the bloodstream be provided for fat?
4. What functions does the large intestine perform?

CHAPTER CHALLENGE QUESTIONS

True-False

Write the correct statement for each statement that is false.

- True or False:* The digestive products of a large meal are difficult to absorb because the absorbent surface of the intestines is relatively small.
- True or False:* Before they can work, some enzymes must be activated by hydrochloric acid or another enzyme.
- True or False:* Bile is an enzyme that is specifically used for the chemical breakdown of fat.
- True or False:* The GI circulation provides a constant supply of water and electrolytes to carry digestive secretions and other substances.
- True or False:* Secretions from the GI accessory organs (i.e., the gallbladder and the pancreas) mix with gastric secretions in the stomach to help with digestion.
- True or False:* One enzyme may work on both carbohydrate and fat breakdown.
- True or False:* Bile is released from the gallbladder in response to a hormonal stimulus.

Multiple Choice

- During digestion, the major muscle action that moves the food mass forward in regular rhythmic waves is called
 - valve contraction.
 - segmentation ring motion.
 - muscle tone.
 - peristalsis.
- Mucus is an important GI secretion because it
 - causes chemical changes in substances to prepare for enzyme action.
 - helps to create the proper degree of acidity for enzymes to act.
 - lubricates and protects the GI lining.
 - helps to emulsify fats for enzyme action.
- Pepsin is
 - produced in the small intestine to act on protein.
 - a gastric enzyme that acts on protein.
 - produced in the pancreas to act on fat.
 - produced in the small intestine to act on fat.
- Bile is an important secretion that is
 - produced by the gallbladder.
 - stored in the liver.
 - an aid to protein digestion.
 - a fat-emulsifying agent.
- The route of fat absorption is
 - the lymphatic system by way of the villi lacteals.
 - directly into the portal blood circulation.
 - with the aid of bile directly into the villi blood capillaries.
 - with the help of protein directly into the portal blood circulation.

Evolve Please refer to the Students' Resource section of this text's Evolve Web site for additional study resources.

REFERENCES

- Food and Nutrition Board, Institute of Medicine. *Dietary reference intakes for calcium, phosphorus, magnesium, vitamin D, and fluoride*. Washington, DC: National Academies Press; 1997.
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- Food and Nutrition Board, Institute of Medicine. *Dietary reference intakes for vitamin C, vitamin E, selenium, and carotenoids*. Washington, DC: National Academies Press; 2000.
- Food and Nutrition Board, Institute of Medicine. *Dietary reference intakes for vitamin A, vitamin K, arsenic, boron, chromium, copper, iodine, iron, manganese, molybdenum, nickel, silicon, vanadium, and zinc*. Washington, DC: National Academies Press; 2001.
- Food and Nutrition Board, Institute of Medicine. *Dietary reference intakes for energy, carbohydrate, fiber, fat, fatty acids, cholesterol, protein, and amino acids*. Washington, DC: National Academies Press; 2002.
- Food and Nutrition Board, Institute of Medicine. *Dietary reference intakes for water, potassium, sodium, chloride, and sulfate*. Washington, DC: National Academies Press; 2004.
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- Kaye CI, Committee on Genetics, Accurso F, et al. Introduction to the newborn screening fact sheets. *Pediatrics*. 2006; 118(3):1304-1312.
- Mayatepek E, Hoffmann B, Meissner T. Inborn errors of carbohydrate metabolism. *Best Pract Res Clin Gastroenterol* 2010;24(5):607-618.

FURTHER READING AND RESOURCES

The following organizations provide up-to-date research and reliable information about matters of the GI tract and metabolism.

The American College of Gastroenterology. www.acg.gi.org

The American Gastroenterological Association.
www.gastro.org

The American Journal of Gastroenterology.
www.amjgastro.com

Metabolism. www.metabolism.com

Nutrition & Metabolism. www.nutritionandmetabolism.com

Duggan S, O'Sullivan M, Feehan S, et al. Nutrition treatment of deficiency and malnutrition in chronic pancreatitis: a review. *Nutr Clin Pract*. 2010;25(4):362-370.

This article will give the reader insight into the complex issues that result when one accessory organ fails to provide the necessary enzymes for normal digestion.