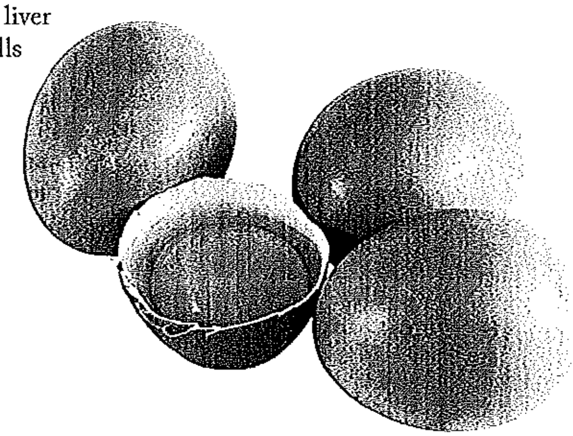
released into the bloodstream. A few larger peptide molecules can escape the digestive process altogether and enter the bloodstream intact. Scientists believe these larger particles may act as hormones to regulate body functions and provide the body with information about the external environment. The larger molecules may also stimulate an immune response and thus play a role in food allergy.

The cells of the small intestine possess separate sites for absorbing different types of amino acids. Amino acids of the same type compete for the same absorption sites. Consequently, when a person ingests a large dose of any single amino acid, that amino acid may limit absorption of others of its general type. The Consumer Corner (page 205) cautions against taking single amino acids as supplements partly for this reason.

Once amino acids are circulating in the bloodstream, they are carried to the liver where they may be used or released into the blood to be taken up by other cells of the body. The cells can then link the amino acids together to make proteins that they keep for their own use or liberate into lymph or blood for other uses. When necessary, the body's cells can also use amino acids for energy.



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KEY POINT The cells of the small intestine complete digestion, absorb amino acids and some larger peptides, and release them into the bloodstream for use by the body's cells.

LO 6.3, 6.4

The Importance of Protein

Amino acids must be continuously available to build the proteins of new tissue. The new tissue may be in an embryo; in the muscles of an athlete in training; in a growing child; in new blood cells needed to replace blood lost in menstruation, hemorrhage, or surgery; in the scar tissue that heals wounds; or in new hair and nails.

Less obvious is the protein that helps to replace worn-out cells and internal cell structures. Each of your millions of red blood cells lives for only three or four months. Then it must be replaced by a new cell produced by the bone marrow. The millions of cells lining your intestinal tract live for only three days; they are constantly being shed and replaced. The cells of your skin die and rub off, and new ones grow from underneath. Nearly all cells arise, live, and die in this way, and while they are living, they constantly make and break down their proteins. In addition, cells must continuously replace their own internal working proteins as old ones wear out. Amino acids conserved from these processes provide a great deal of the required raw material from which new structures are built. The entire process of breakdown, recovery, and synthesis is called **protein turnover.**

Each day, about a quarter of the body's available amino acids are irretrievably diverted to other uses, such as being used for fuel. For this reason, amino acids from food are needed each day to support the new growth and maintenance of cells and to make the working parts within them. The following sections spell out some of the critical roles that proteins play in the body.

KEY POINT The body needs dietary amino acids to grow new cells and to replace worn-out ones.

The Roles of Body Proteins

Only a sampling of the many roles proteins play can be described here, but these illustrate their versatility, uniqueness, and importance in the body. One important role was already mentioned: regulation of gene expression. Others range from digestive enzymes and antibodies to tendons and ligaments, scars, filaments of hair, the materials of nails, and more. No wonder their discoverers called proteins the primary material of life.

protein turnover the continuous breakdown and synthesis of body proteins involving the recycling of amino acids.

Providing Structure and Movement A great deal of the body's protein (about 40 percent) exists in muscle tissue. Specialized muscle protein structures allow the body to move. In addition, muscle proteins can release some of their amino acids should the need for energy become dire, as in starvation. These amino acids are integral parts of the muscle structure and their loss exacts a cost of functional protein. Other structural proteins confer shape and strength on bones, teeth, skin, tendons, cartilage, blood vessels, and other tissues. All are important to the workings of a healthy body.

Building Enzymes, Hormones, and Other Compounds Among proteins formed by living cells, enzymes are metabolic workhorses. An enzyme acts as a **catalyst:** it speeds up a reaction that would happen anyway, but much more slowly. Thousands of enzymes reside inside a single cell, and each one facilitates a specific chemical reaction. Figure 6-9 shows how a hypothetical enzyme works—this one synthesizes a compound from two chemical components. Other enzymes break compounds apart into two or more products or rearrange the atoms in one kind of compound to make another. A single enzyme can facilitate several hundred reactions in a second.

The body's **hormones** are messenger molecules, and many of them are made from amino acids. Various body glands release hormones when changes occur in the internal environment; the hormones then elicit tissue responses necessary to restore normal conditions. For example, the familiar pair of hormones, insulin and glucagon, oppose each other to maintain blood glucose levels. Both are built of amino acids. For interest, Figure 6-10 shows how many amino acids are linked in sequence to form human insulin. It also shows how certain side groups attract one another to complete the insulin molecule and make it functional.

CONCEPT LINK 6-3
Insulin and glucagon were topics of Chapter 4, page 127.

- Recall from Chapter 5 that other hormones are made from lipids.

In addition to serving as building blocks for proteins, amino acids also perform other tasks in the body. For example, the amino acid tyrosine forms parts of the neurotransmitters epinephrine and norepinephrine, which relay messages throughout the nervous system. The body also uses tyrosine to make the brown pigment melanin, which is responsible for skin, hair, and eye color. Tyrosine is also converted into the thyroid hormone **thyroxine,** which regulates the body's metabolism. Another amino acid, tryptophan, serves as starting material for the neurotransmitter **serotonin** and the vitamin niacin.

CONCEPT LINK 6-4
Neurotransmitters were introduced in Chapter 3, page 76.

- The vitamin niacin is discussed in Chapter 7.

Building Antibodies Of all the proteins in living organisms, the **antibodies** best demonstrate that proteins are specific to one organism. Antibodies distinguish foreign particles (usually proteins) from all the proteins that belong in "their" body. When they recognize an intruder, they mark it as a target for attack. The foreign protein may be part of a bacterium, a virus, or a toxin, or it may be present in a food that causes an allergic reaction.

Each antibody is designed to help destroy one specific invader. An antibody active against one strain of influenza is of no help to a person ill with another strain. Once the body has learned how to make a particular antibody, it remembers. The next time the body encounters that same invader, it destroys the invader even more rapidly. In

catalyst a substance that speeds the rate of a chemical reaction without itself being permanently altered in the process. All enzymes are catalysts.

hormones chemical messengers secreted by a number of body organs in response to conditions that require regulation. Each hormone affects a specific organ or tissue and elicits a specific response. Also defined in Chapter 3.

thyroxine (thigh-ROX-in) a principle peptide hormone of the thyroid gland that regulates the body's rate of energy use.

serotonin (SARE-oh-TONE-in) a compound related in structure to (and made from) the amino acid tryptophan. It serves as one of the brain's principal neurotransmitters.

antibodies (AN-te-bod-ees) large proteins of the blood, produced by the immune system in response to an invasion of the body by foreign substances (antigens). Antibodies combine with and inactivate the antigens. Also defined in Chapter 3.

FIGURE 6-9 **Enzyme Action**

Compounds A and B are attracted to the enzyme's active site and park there for a moment in the exact position that makes the reaction between them most likely to occur. They react by bonding together and leave the enzyme as the new compound, AB.

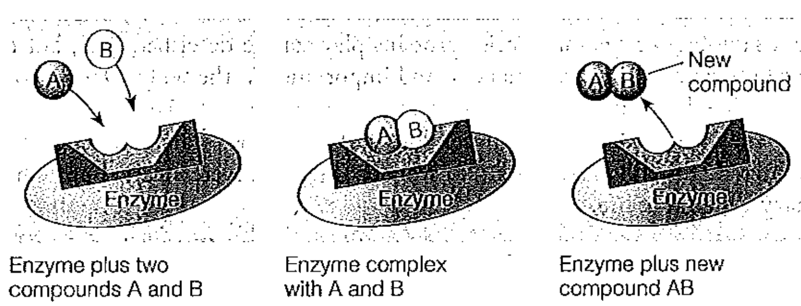
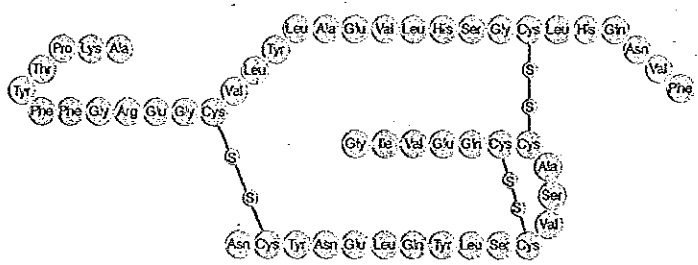


FIGURE 6-10 Amino Acid Sequence of Human Insulin

This picture shows a refinement of protein structure not mentioned in the text. The amino acid cysteine (cys) has a sulfur-containing side group. The sulfur groups on two cysteine molecules can bond together, creating a bridge between two protein strands or two parts of the same strand. Insulin contains three such bridges.



other words, the body develops **immunity** to the invader. This molecular memory underlies the principle of immunizations, injections of drugs made from destroyed and inactivated microbes or their products that activate the body's immune defenses. Some immunities are lifelong; others, such as that to tetanus, must be "boosted" at intervals.

CONCEPT LINK 6-5

A discussion of the immune system is found in Chapter 3, pages 76–77.

Transporting Substances A large group of proteins specialize in transporting other substances, such as lipids, vitamins, minerals, and oxygen around the body. To do their jobs, such substances must travel within the bloodstream, into and out of cells, or around the cellular interiors. Two familiar examples are the protein hemoglobin that carries oxygen from the lungs to the cells and the lipoproteins that transport lipids in the watery blood.

Maintaining Fluid and Electrolyte Balance Proteins help to maintain the **fluid and electrolyte balance** by regulating the quantity of fluids in the compartments of the body. To remain alive, cells must contain a constant amount of fluid. Too much can cause them to rupture; too little makes them unable to function. Although water can diffuse freely into and out of cells, proteins cannot; and proteins attract water.

By maintaining stores of internal proteins and also of some minerals, cells retain the fluid they need. By the same mechanism, fluid is kept inside the blood vessels by proteins too large to move freely across the capillary walls. The proteins attract water and hold it within the vessels, preventing it from freely flowing into the spaces between the cells. Should any part of this system begin to fail, too much fluid will soon collect in the spaces between the cells of tissues, causing **edema.**

- The control of water's location by electrolytes is discussed further in Chapter 8.

SPL/Photo Researchers, Inc.

Edema results when body tissues fail to control the movement of water.

immunity protection from or resistance to a disease or infection by development of antibodies and by the actions of cells and tissues in response to a threat.

fluid and electrolyte balance the distribution of fluid and dissolved particles among body compartments (see also Chapter 8).

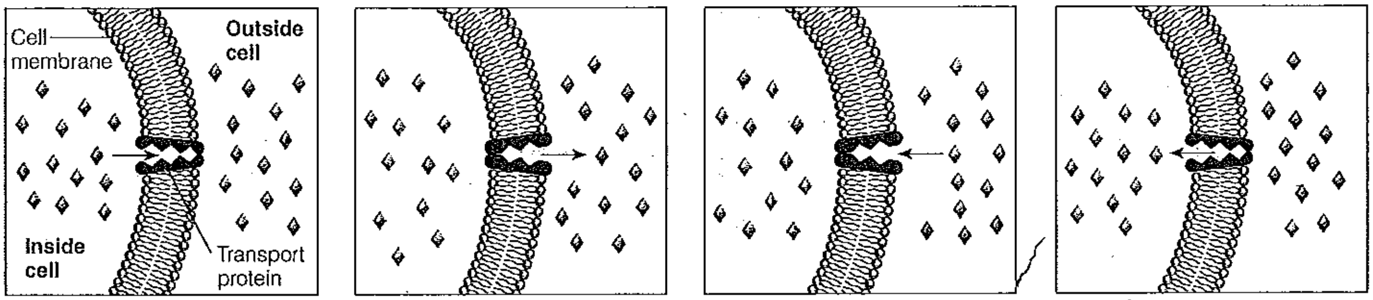
edema (eh-DEEM-uh) swelling of body tissue caused by leakage of fluid from the blood vessels; seen in protein deficiency (among other conditions).

FIGURE 6-11

ANIMATED!

Proteins Transport Substances Into and Out of Cells

A transport protein within the cell membrane acts as a sort of two-door passageway—substances enter on one side and are released on the other, but the protein never leaves the membrane. The protein differs from a simple passageway in that it actively escorts the substances in and out of cells; therefore, this form of transport is often called active transport.



Molecule enters protein from inside cell. | Protein changes shape; molecule exits protein outside the cell. | Molecule enters protein from outside cell. | Molecule exits protein; proper balance restored.

Not only is the quantity of the body fluids vital to life but so also is their composition. Transport proteins in the membranes of cells also help maintain this composition by continuously transferring substances into and out of cells (see Figure 6-11). For example, sodium is concentrated outside the cells, and potassium is concentrated inside. A disturbance of this balance can impair the action of the heart, lungs, and brain, triggering a major medical emergency. Cell proteins avert such a disaster by holding fluids and electrolytes in their proper chambers.

Maintaining Acid-Base Balance Normal processes of the body continually produce **acids** and their opposite, **bases**, that must be carried by the blood to the organs of excretion. The blood must do this without allowing its own **acid-base balance** to be affected. This feat is another trick of the blood proteins, which act as **buffers** to maintain the blood's normal pH. The protein buffers pick up hydrogens (acid) when there are too many in the bloodstream and release them again when there are too few. The secret is that negatively charged side chains of amino acids can accommodate additional hydrogens, which are positively charged.

Blood pH is one of the most rigidly controlled conditions in the body. If blood pH changes too much, **acidosis** or the opposite basic condition, **alkalosis**, can cause coma or death. These conditions constitute medical emergencies because of their effect on proteins. When the proteins' buffering capacity is filled—that is, when they have taken on all the acid hydrogens they can accommodate—additional acid pulls them out of shape, denaturing them and disrupting many body processes.

Blood Clotting To prevent dangerous blood loss, special blood proteins respond to an injury by clotting the blood. In an amazing series of chemical events, these proteins form a stringy net that traps blood cells to form a clot. The clot acts as a plug to stem blood flow from the wound. Later, as the wound heals, the protein collagen finishes the job by replacing the clot with scar tissue.

The final function of protein, providing energy, depends upon some metabolic adjustments, as described in the next section. Table 6-1 provides a summary of the functions of proteins in the body.

Providing Energy and Glucose Only protein can perform all the functions just described, but protein will be surrendered to provide energy if need be. Under conditions of inadequate energy or carbohydrate, protein breakdown speeds up, as the next section explains.[9]

KEY POINT Proteins provide structure and movement; serve as enzymes, hormones, and antibodies; provide molecular transport,

acids compounds that release hydrogens in a watery solution.

bases compounds that accept hydrogens from solutions.

acid-base balance equilibrium between acid and base concentrations in the body fluids.

buffers compounds that help keep a solution's acidity or alkalinity constant.

acidosis (acid-DOH-sis) the condition of excess acid in the blood, indicated by a below-normal pH (*osis* means "too much in the blood").

alkalosis (al-kah-LOH-sis) the condition of excess base in the blood, indicated by an above-normal blood pH (*alka* means "base"; *osis* means "too much in the blood").

fluid and electrolyte regulation, buffers for blood; contribute to blood clotting, energy supplies, and glucose for the body.

Amino Acids to Glucose

The body must have energy to live from moment to moment, so obtaining that energy is a top priority. Not only can amino acids supply energy but many of them can be converted to glucose, as fatty acids can never be. Thus, if the need arises, protein can help to maintain a steady blood glucose level and serve the glucose need of the brain.

When amino acids are degraded for energy or converted into glucose, their nitrogen-containing amine groups are stripped off and used elsewhere or are incorporated by the liver into **urea** and sent to the kidneys for excretion in the urine. The fragments that remain are composed of carbon, hydrogen, and oxygen, as are carbohydrate and fat, and can be used to build glucose or fatty acids or can be metabolized like them.

Protein Lack and Abundance Glucose is stored as glycogen and fat as triglycerides, but no specialized storage compound exists for protein. Body protein is present only as the active working molecular and structural components of body tissues. When protein-sparing energy from carbohydrate and fat is lacking and the need becomes urgent, as in starvation, prolonged fasting, or severe calorie restriction, the body must dismantle its tissue proteins to obtain amino acids for building the most essential proteins and for energy. Each protein is taken in its own time: first, small proteins from the blood; then, proteins from the muscles, liver, and other organs. Thus, energy deficiency (starvation) always incurs wasting of lean body tissue as well as loss of fat.

When amino acids are oversupplied, the body cannot store them. It has no choice but to remove and excrete their amine groups and then use the residues in one of three ways: to meet immediate energy needs, to make glucose for storage as glycogen, or to make fat for energy storage.[10] The body readily converts amino acids to glucose. The body also possesses enzymes to convert amino acids into fat and can produce fatty acids for storage as triglycerides in the fat tissue. An indirect contribution of amino acids to fat stores also exists—the body speeds up its use of amino acids for fuel, burning them instead of fat, which is then abundantly available for storage in the fat tissue.

The similarities and differences of the three energy-yielding nutrients should now be clear. Carbohydrate offers energy; fat offers concentrated energy; and protein can offer energy plus nitrogen (see Figure 6-12).

FIGURE 6-12 Three Different Energy Sources

Carbohydrate offers energy; fat offers concentrated energy; and protein, if necessary, can offer energy plus nitrogen. The compounds at the left yield the 2-carbon fragments shown at the right. These fragments oxidize quickly in the presence of oxygen to yield carbon dioxide, water, and energy.

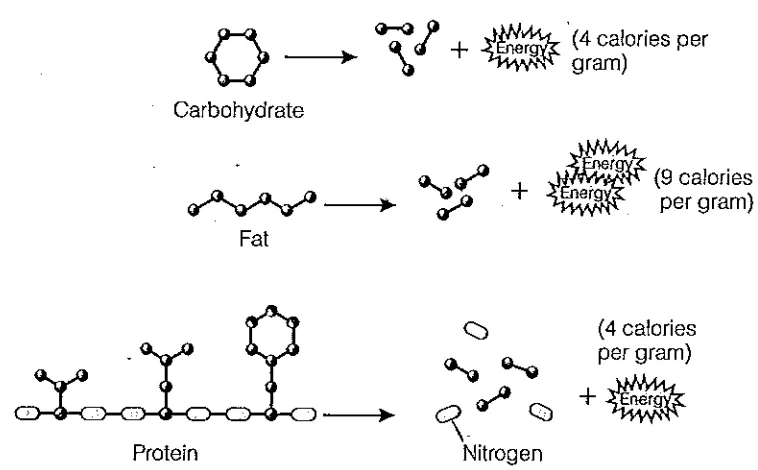


TABLE 6-1 Summary of Protein Functions

- *Acid-base balance.* Proteins help maintain the acid-base balance of various body fluids by acting as buffers.
- *Antibodies.* Proteins form the immune system molecules that fight diseases.
- *Blood clotting.* Proteins provide the netting on which blood clots are built.
- *Energy and glucose.* Proteins provide some fuel for the body's energy needs.
- *Enzymes.* Proteins facilitate needed chemical reactions.
- *Fluid and electrolyte balance.* Proteins help to maintain the water and mineral composition of various body fluids.
- *Gene expression.* Proteins associate and interact with DNA, regulating gene expression.
- *Hormones.* Proteins regulate body processes. Some hormones are proteins or are made from amino acids.
- *Structure.* Proteins form integral parts of most body tissues and confer shape and strength on bones, skin, tendons, and other tissues. Structural proteins of muscles allow body movement.
- *Transportation.* Proteins help transport needed substances, such as lipids, minerals, and oxygen, around the body.

• More about the effects of fasting in Chapter 9.

urea (yoo-REE-uh) the principal nitrogen-excretion product of protein metabolism; generated mostly by removal of amine groups from unneeded amino acids or from amino acids being sacrificed to a need for energy.

The Fate of an Amino Acid To review the body's handling of amino acids, let us follow the fate of an amino acid that was originally part of a protein-containing food. When the amino acid arrives in a cell, it can be used in one of several ways, depending on the cell's needs at the time:

- The amino acid can be used as is to build part of a growing protein.
- The amino acid can be altered somewhat to make another needed compound, such as the vitamin niacin.
- The cell can dismantle the amino acid in order to use its amine group to build a different amino acid. The remainder can be used for fuel or, if fuel is abundant, converted to glucose or fat.

- Amino acids in a cell can be:
  - *Used to build protein.*
  - *Converted to other amino acids or small nitrogen-containing compounds.*

In a cell that is starved for energy and has no glucose or fatty acids, the cell strips the amino acid of its amine group (the nitrogen part) and uses the remainder of its structure for energy. The amine group is excreted from the cell and then from the body in the urine. In a cell that has a surplus of energy and amino acids, the cell takes the amino acid apart, excretes the amine group, and uses the rest to meet immediate energy needs or converts it to glucose or fat for storage.

- Stripped of their nitrogen, amino acids can be:
  - *Burned as fuel.*
  - *Converted to glucose or fat.*

When not used to build protein or make other nitrogen-containing compounds, amino acids are "wasted" in a sense. This wasting occurs under any of four conditions:

1. When the body lacks energy from other sources.
2. When the diet supplies more protein than the body needs.
3. When the body has too much of any single amino acid, such as from a supplement.
4. When the diet supplies protein of low quality, with too few essential amino acids, as described in the next section.

- Amino acids are wasted when:
  - *Energy is lacking.*
  - *Protein is overabundant.*
  - *An amino acid is oversupplied in supplement form.*
  - *The protein is of low quality (too few essential amino acids).*

To prevent the wasting of dietary protein and permit the synthesis of needed body protein, the dietary protein must be of adequate quality; it must supply all essential amino acids in the proper amounts; it must be accompanied by enough energy-yielding carbohydrate; and fat must be present to permit the dietary protein to be used as such.

KEY POINT Amino acids can be metabolized to protein, nitrogen plus energy, glucose, or fat. They will be metabolized to protein only if sufficient energy is present from other sources. The nitrogen part is removed from each amino acid, and the resulting fragment is oxidized for energy. No storage form of amino acids exists in the body.

LO 6.5

Food Protein: Need and Quality

A person's response to dietary protein depends on many factors. To know whether, say, 60 grams of a particular protein is enough to meet a person's daily needs, one must consider the effects of factors discussed in this section, some pertaining to the body and some to the nature of the protein.

How Much Protein Do People Really Need?

The DRI recommendation for protein intake is designed to cover the need to replace protein-containing tissue that healthy adults lose and wear out every day. Therefore, it depends on body size: larger people have a higher protein need. For adults of