FUNCTION OF THE HUMAN BODY

GUYTON

THIRD EDITION

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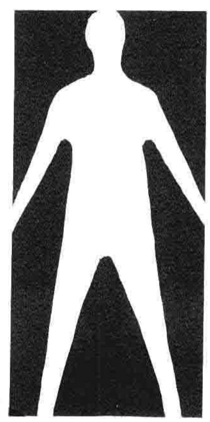

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PREFACE

An author finds his reward in the degree of acceptance of his work. Therefore, it has been most gratifying that the first edition of this textbook, *Function of the Human Body,* received wide usage and more particularly that usage of the second edition multiplied several times more. Such gratification can lead an author only to work much harder to make each succeeding edition still more valuable to the reader. In view of this, very large segments of the text have been recast or extensively revised. In addition, new figures have been added while a large share of the older ones have been modified to improve their quality. And because physiology is in a dynamic stage of discovery, our knowledge in many areas has changed markedly in the last five years. These changes are evident everywhere in the text.

The purpose of this text is to provide a survey of the major facts and theories in the field of human physiology. Yet the field is so great that it has been possible to cover only a small fraction of it. Therefore, it has been necessary to choose carefully which facts of function are most important and, where precise knowledge of function is lacking, to choose as intelligently as possible the most applicable theories. A special attempt has been made to distinguish fact from theory but not to burden the reader with intricate and insignificant details which more properly belong in a reference textbook of physiology.

Still more, it has been my desire to present the basic philosophy of function of the human body, to demonstrate the beauty of organization of the parts of the body and to fit these together into an overall whole—a thinking, sensing, functioning human being capable of living almost automatically and yet capable of immense diversity that characterizes only higher forms of life. There is no machine yet designed (or ever to be designed) that has more intricacy, more excitement, or more majesty than the human body. Therefore, I hope that it will be with pleasure as well as with instructiveness that the reader learns how his body functions.

A text such as this requires work by many different people, not the least among whom are the teachers who send suggestions to the author and especially who point out errors either of fact or of presentation. Feedback of this type helped immensely in making the second edition better than the first and I hope also in making the third edition still much better. I wish also to express my appreciation to Mrs. Billie Howard for her superb secretarial help in preparing this third edition, to Mrs. Carolyn Hull for drawing most of the figures, and to the staff of the W. B. Saunders Company for their continued excellence in production of this book.

ARTHUR C. GUYTON

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SECTION ONE

INTRODUCTION: CELL PHYSIOLOGY

CHAPTER 1

INTRODUCTION TO HUMAN PHYSIOLOGY

What is physiology? We could spend the remainder of our lives attempting to define this word alone, for physiology is the study of life itself. It is the study of function of all parts of living organisms, as well as of the whole organism. It attempts to discover answers to such questions as: How and why do plants grow? What makes bacteria divide again and again? How do fish obtain oxygen from the sea and what use do they make of it? How is food digested? What is the nature of the thinking process in the brain?

Even small viruses weighing a million times less than bacteria have the characteristics of life, for they feed on their surroundings, they grow and reproduce, and they excrete by-products. These very minute living structures are the subject of the simplest type of physiology, *viral physiology.* Physiology becomes progressively more complicated and vast as it extends through the study of higher and higher forms of life such as bacteria, cells, plants, lower animals, and, finally, human beings. It is obvious, then, that the subject of this book, "human physiology," is but a small part of this vast discipline.

As small children we begin to wonder what enables people to move, how it is possible for them to talk, how they can see the expanse of the world and feel the objects about them, what happens to the food they eat, how they derive from food the energy for locomotion and other types of bodily activity, by what process they reproduce other beings like themselves so that life goes on, generation after generation. All these and other human activities make up *life.* Physiology attempts to explain them and hence to explain life itself.

ROLE OF THE CELL IN THE HUMAN BODY

One hundred trillion cells make up the human body. Each of these is a living unit in itself, capable of existing, performing chemical reactions, contributing its part to the overall function of the body, and in most instances reproducing itself.

The cells are the building blocks of the organs, and each of the organs performs its own specialized function. One will appreciate the importance of the cell when he realizes that many more millions of years went into the evolutionary development of the cell than into the evolution from the cell to the human being. Therefore, before one can understand how any one of the organs functions or how the organs function together to maintain life, it is prerequisite that he understand the inner workings of the cell itself. The next few chapters will be devoted entirely to discussion of basic cellular function, and throughout the remainder of this book we will allude again and again to cellular function as the basis of organ and system operation.

The Internal Environment and Homeostasis

For the cells of the body to continue living, there is one major requirement: the composition of the body fluids that bathe the outside of the cells must be controlled very exactly from moment to moment and day to day, with no single important constituent ever varying more than a few per cent. Indeed, cells can live even after removal from the body if they are placed in a fluid bath that contains the same constituents and has the same physical conditions as those of the body fluids. Claude Bernard, the great nineteenth century physiologist who originated much of our modern physiological thought, called the extracellular fluids that surround the cells the *milieu interne,* the "internal environment," and Walter Cannon, another great physiologist of the first half of this century, referred to the maintenance of constant conditions in these fluids as *homeostasis.*

Thus, at the very outset of our discussion of physiology of the human body, we are beset with a major problem. How does the body maintain the required constancy of the internal environment? The answer to this is that almost every organ plays some role in the control of one or more of the fluid constituents. For instance, the *circulatory system,* composed of the *heart* and *blood vessels,* transports blood throughout the body; water and dissolved substances diffuse back and forth between the blood and the fluids that surround the cells. Thus, the circulatory system keeps the fluids of all parts of the body constantly mixed. This function of the circulatory system is so effective that hardly any portion of fluid in any part of the body remains unmixed with the other fluids of the body more than a few minutes at a time. The *respiratory system* transfers oxygen from the air to the blood, and the blood in turn transports the oxygen to all the tissue spaces surrounding the cells, thus maintaining the level of oxygen that is required for life by all the cells. The carbon dioxide excreted by the cells enters the tissue fluids, then becomes mixed with the blood and is finally removed through the lungs.

The *digestive system* performs a similar function for other nutrients besides oxygen; it processes nutrients which are then absorbed into the blood and are rapidly transported throughout the body fluids where they can be used by the cells. The *liver,* the *endocrine glands,* and some of the other organs participate in what is collectively known as *intermediary metabolism,* which converts many of the nutrients absorbed from the gastrointestinal tract into substances that can be used directly by the cells. The *kidneys* remove the remains of the nutrients after their energy has been extracted by the cells, and other organs provide for *hearing, feeling, tasting, smelling,* and *seeing,* all of which aid the animal in his search for and selection of food and also help him to protect himself from dangers so that he can perpetuate the almost Utopian internal environment in which his cells continue their life processes.

Thus, we can emphasize once again that organ functions of the body depend on individual functions of cells, and, in turn, sustained life of the cells depends on maintenance of an appropriate fluid environment.

ORGANS AND SYSTEMS OF THE HUMAN BODY

The Skeleton and Its Muscles

Figure 1 illustrates the skeleton with some of its muscles attached. Each joint of the skeleton is enveloped by a loose *capsule,* and the space within the capsule and between the two respective bones is the *joint cavity.* In the joint cavities is a thick, slippery fluid containing hyaluronic acid which lubricates the joints, promoting ease of movement. On the sides of each capsule are strong fibrous *ligaments* that keep the joints from pulling apart. Often the ligaments are only on two sides of the joint, which allows the joint to move freely in one direction but not so freely in another direction. Other

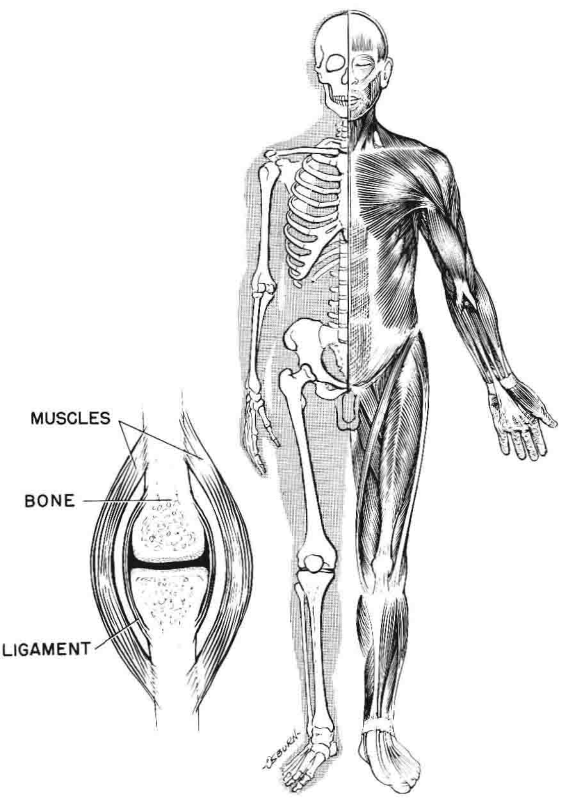

Figure 1. The skeletal and muscular systems of the human body.

joints, particularly those of the spine, hips, and shoulders, not having very restrictive ligaments, can move in almost any direction; that is, they can bend forward, backward, and to either side, or they can even be rotated. In these instances, loose ligaments merely limit the degree of motion to prevent excessive movement in any one direction.

Muscles move the limbs and other parts of the body in the directions allowed by the ligaments. In the case of movement at the knee joint, for instance, one major muscle is on the front and several muscles are on the back of the joint. Contraction of the anterior muscle pulls the lower leg forward, while contraction of the posterior muscles pulls it backward. There is a similar arrangement of muscles anteriorly and posteriorly about the ankle, except that the ligaments of the ankle allow the ankle joints to move also from side to side, and additional muscles are available to provide the sidewise movements. The muscles of the spine are especially interesting because, contrary to what might be expected, the back muscles are not just a few very large muscles, but are composed of about one hundred different individual muscles each one of which performs a specific function: one rotates an adjacent vertebra while a second one flexes the vertebra forward, a third backward, and so on. This is analogous to the arrangement of the centipede, for each segment can bend independently of all the others. The joint connecting the head to the spinal column is also supplied with many separate muscles arranged on all sides so that the head can be rotated from side to side or bent in any direction.

In summary, then, the skeleton is literally a bag of bones which can be contorted into many different configurations. Each bone has its own function, and the limitations of angulation of each joint are decreed by the ligaments. The knee joint bends in only one direction, the ankle joint in two, the hip joint in two directions plus an additional rotary motion; and, in general, at least two muscles are available for each motion that the ligaments of a joint allow, one for each of the two directions of movement.

The muscles themselves are composed of long *muscle fibers*. Usually many thousands of these fibers are oriented side by side like the threads in a skein of wool. At each end of the muscle, the muscle fibers fuse with strong *tendon fibers* that form a bundle called the *muscle tendon*. The muscle tendons in turn penetrate and fuse with the bones on the two sides of the respective joint so that any pull exerted will effect appropriate movement.

All muscles are not exactly alike in size and appearance; for instance, the smallest skeletal muscle of the body, the stapedius, is a minute muscle in the middle ear only a few millimeters long, while the longest muscle, the sartorius, extends almost two feet down the entire length of the thigh, connecting the pelvic bone with the lower leg. Some muscles, such as those of the abdominal wall, are arranged in thin sheets, while others are round, cigar-shaped structures, for example, the biceps which lifts the lower arm and the gastrocnemius which pulls the foot down when one wishes to stand on tiptoes.

The precise method by which muscle fibers contract is still not completely clear, but we do know that signals arriving in the muscles through nerves cause each fiber to shorten for a brief instant, allowing the entire muscle belly to contract and thereby to perform its function.

The Nervous System

The nervous system, illustrated in Figure 2, is composed of the brain, the spinal cord, and the peripheral nerves that extend throughout the body. A major function of the nervous system is to control many of the bodily activities, especially those of the muscles, but to exert this control intelligently the brain must be apprised continually of the body's surroundings. To perform these varied activities, the nervous system is composed of two separate portions, the *sensory portion* which reports and analyzes the nature of conditions around the body, and the *motor portion* which controls the muscles.

The sensory portion operates through the senses of sight, hearing, smell, taste, and feel. The sense of feel is actually many different senses, for one can feel light touch, pin pricks, pressure, pain, vibration, position of the joints, tightness of the muscles, and tension on the tendons.

Once information has been relayed to the brain from all the senses, the brain then determines what movement, if any, is most suitable, and the muscles are called into action to implement the decision.

One of the most important functions of the nervous system is to regulate walking. In walking, the body must be supported against gravity, the legs must move rhythmically in a walking motion, equilibrium must be maintained, and the direction of movement of the limbs must be guided. Therefore, the initiation and control of locomotion are very complex functions of the nervous system and require the services of major portions of the brain.

The autonomic nervous system. The autonomic nervous system, which is really part of the motor portion of the nervous system, regulates many of the internal functions of the body. It operates principally by causing contraction or relaxation of a type of muscle called *smooth muscle*, which constitutes major portions of many of the internal organs. Smooth muscle fibers are much smaller than skeletal muscle fibers, and they usually are arranged in large muscular sheets. For instance, the gastrointestinal tract, the urinary bladder, the uterus, the biliary ducts, and the blood vessels are all composed mainly of smooth muscle sheets rolled into tubular or spheroid structures. Some of the autonomic nerves cause the muscles of these organs to contract while others cause relaxation.

The autonomic nerves also regulate secretion by many of the glands in the gastrointestinal tract and elsewhere in the body, and at times their nerve endings even secrete hormones that can increase or decrease the rates of chemical reactions in the body's tissues.

Finally, the autonomic nervous system helps to control the heart, which is composed of *cardiac muscle*, a type of muscle intermediate between smooth muscle and skeletal muscle. Stimulation of the so-called *sympathetic fibers* causes the rate and force of contraction of the heart to increase, whereas stimulation of the *parasympathetic* fibers causes the opposite effects.

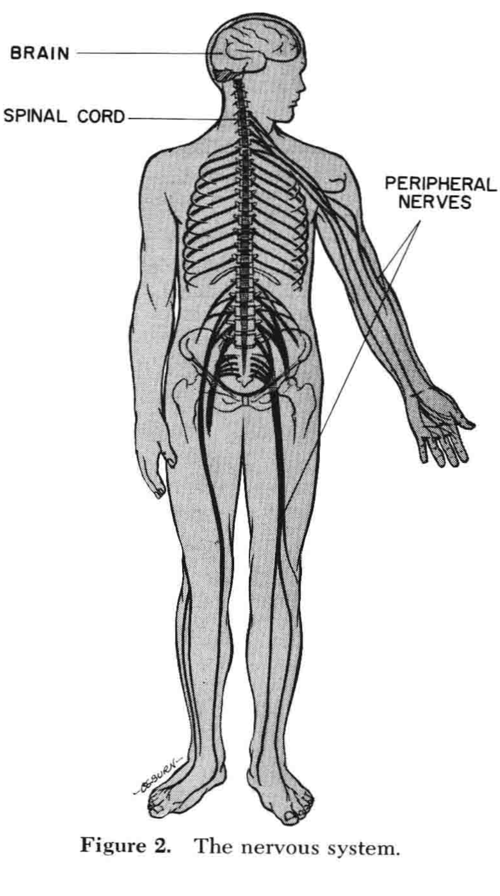

Figure 2. The nervous system.

In summary, the autonomic nervous system helps to control most of the body's internal functions.

The Circulatory System

The circulatory system, illustrated in Figure 3, is composed mainly of the heart and blood vessels. The heart consists of two separate pumps arranged side by side. The first pump forces blood into the lungs. From them, the blood returns to the second pump to be forced then into the *systemic arteries* which transport it through the body. From the arteries it flows into the *capillaries*, then into the *veins* and finally back to the heart, thus making a complete circuit. Circulating around and around through the body, the blood acts as a transportation system for conducting various chemical substances from one place to another. It is the circulatory system that carries nutrients to the tissues and then carries excretory products away from the tissues.

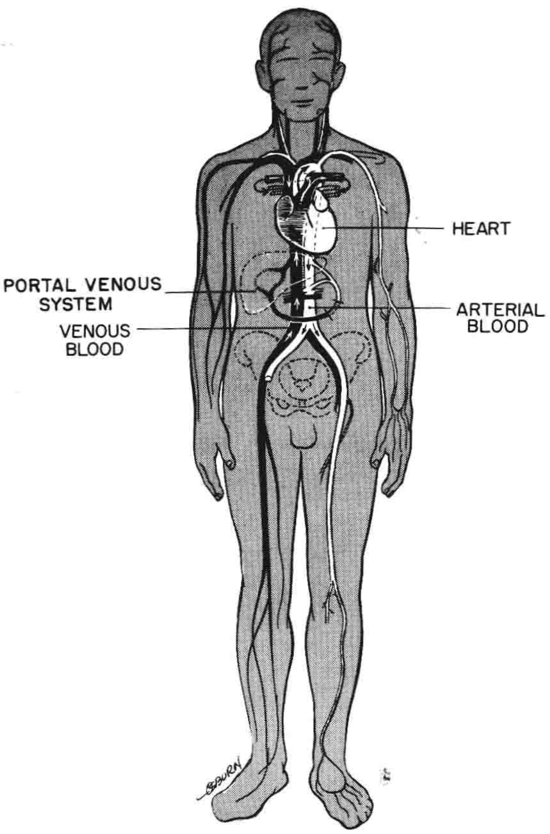

Figure 3. The circulatory system; heart and major vessels.

The capillaries are porous, allowing fluid and nutrients to diffuse into the tissues and excreta from the cells to reenter the blood.

THE LYMPHATICS. Large particles, such as old debris of dead tissues, protein molecules, and dead bacteria cannot pass from the tissues directly into the blood through the small pores of the capillaries. A special accessory circulatory system known as the *lymphatic system* takes care of these materials. Lymphatic vessels originate in small *lymphatic capillaries* which lie beside the blood capillaries, and *lymph,* which is fluid derived from the spaces between the cells, flows along the lymphatic vessels up to the neck where these vessels empty into the neck veins. The lymphatic capillaries are extremely porous so that large particles can enter the lymphatic system and be transported by the lymph. At several points the lymphatic vessels pass through *lymph nodes* where most large particles are filtered out and where bacteria are engulfed and digested by special cells called *reticuloendothelial* cells.

The Respiratory System

Figure 4 is a diagram of the respiratory system, showing the two fundamental portions of this system: (1) the air passages and (2) the blood vessels of the lungs. Air is moved in and out of the lungs by contraction and relaxation of the respiratory muscles, and blood flows continually through the vessels. Only a very thin membrane separates the air from the blood, and since this membrane is porous to gases it allows free passage of oxygen into the blood and of carbon dioxide from the blood into the air.

Oxygen is one of the nutrients needed by the body's tissues. It is carried by the blood and tissue fluids to the cells where it combines chemically with foods to release energy. This in turn is used to promote muscle contraction, secretion of digestive juices, conduction of signals along nerve fibers, and synthesis of many substances needed for growth and function of cells.

When oxygen combines with foods to liberate energy, carbon dioxide is formed. This is carried by tissue fluids to the blood and by the blood to the lungs. Then, the carbon dioxide diffuses from the blood into the lung air to be breathed out into the atmosphere.

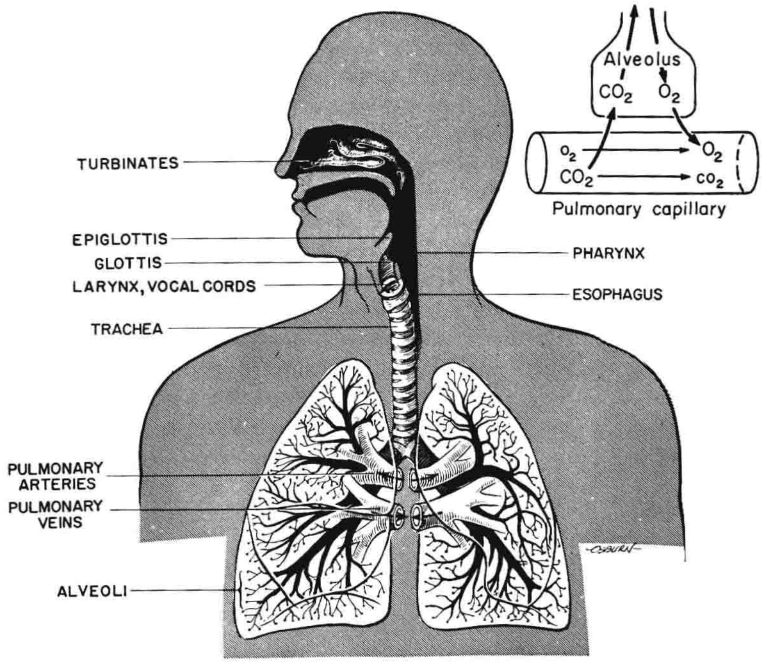

Figure 4. The respiratory system.

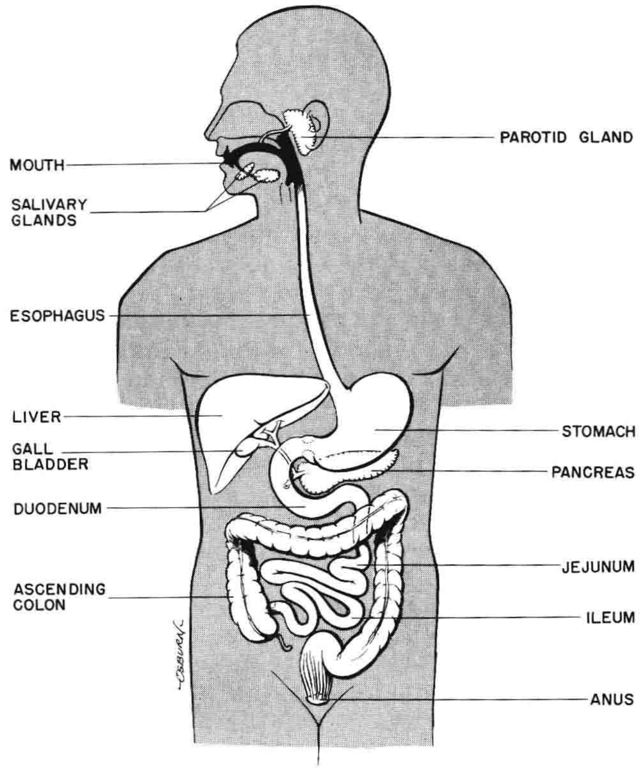

Figure 5. The digestive system.

The Gastrointestinal System

The digestive system is illustrated in Figure 5. Food after being swallowed enters the stomach, then the duodenum, the jejunum, the ileum, and the large intestine, finally to be defecated through the anus. Those portions of the food valuable to the body are chemically and physically extracted by the process of *digestion,* and are transferred into the blood by the process of *absorption.* Along the entire extent of the gastrointestinal tract, special substances are secreted into the gut either continuously or when food is present. These secretions contain *digestive enzymes* which cause the foods to split into chemicals small enough to pass through the pores of the intestinal membrane into underlying capillary and lymphatic vessels. Thence the digestive products enter the circulating blood to be transported and used where they may be needed.

Metabolic Systems

METABOLISM AND GROWTH. The term *metabolism* means simply the chemical reactions that occur in the animal organism. These reactions occur inside the individual cells which make up the tissues, and their functions are to provide energy to perform the bodily activities and to build new structures. It is because of the metabolic processes that the cells grow larger and more numerous. The metabolism of special cells allows them to form structures such as bones and fibrous tissue, enlarging the entire animal. Thus, metabolism is the basis not only for the energy needed by the body but for growth itself.

Intermediary metabolism. Many of the foods entering the blood from the digestive tract can be used by the body's tissues without alteration, but some tissues require special chemicals which are not normally found in the food. To supply these, much of the absorbed food passes to special organs where it is changed into new substances needed by the cells. This process is called *intermediary metabolism.*

THE LIVER. The liver is one of the internal organs especially adapted for intermediary metabolism and storage. It can split fats and proteins into smaller substances so that the tissues can use them for energy, and it forms products needed for blood coagulation, for transport of fat, for immunity to infection, and for many other purposes. The liver is also capable of storing large quantities of fats, carbohydrates, and even proteins and then releasing these foods when the tissues need them. An animal can live for only a few hours without a liver.

CONTROL OF METABOLISM BY THE HORMONES. Metabolism is an inherent function of every cell of the body. However, the rate of metabolism in each respective cell is very often increased or decreased by the controlling action of *hormones* secreted by *endocrine glands* in different parts of the body. The *thyroid gland,* located in the neck, secretes *thyroxine* which acts on all cells of the body to increase the rate of most metabolic reactions. *Epinephrine* and *norepinephrine,* two hormones secreted by the *adrenal medullas,* also increase the rate of metabolism in all cells. The *ovaries* secrete *estrogens* and *progesterone,* and the *testes* secrete *testosterone,* which helps to control metabolism in the sex organs of the female and male, respectively. *Insulin,* secreted by the *pancreas,* a gland located behind and beneath the stomach, increases the utilization of carbohydrates and decreases the utilization of fats in all the tissues. *Adrenocortical hormones* secreted by the two *adrenal cortices,* located at the upper poles of the kidneys, help to convert proteins to carbohydrates, and they control the passage of proteins, salts, and perhaps other substances through the cell walls. Finally, *parathyroid hormone,* secreted by four minute *parathyroid glands* located behind the thyroid gland in the neck, controls the amount of calcium in the blood by removing calcium from the bones when it is needed and by allowing more deposition in the bones when it is not needed.

The Excretory System

The *kidneys,* illustrated in Figure 6, constitute an excretory system for ridding the blood of unwanted substances. Most of the substances are the end-products of metabolic reactions, including mainly urea, uric acid, creatinine, phenols, sulfates, and phosphates. If they were allowed to collect in the blood in large quantities, the "ashes of the cellular fires" would soon "smother the flames" themselves so that no further metabolic re-

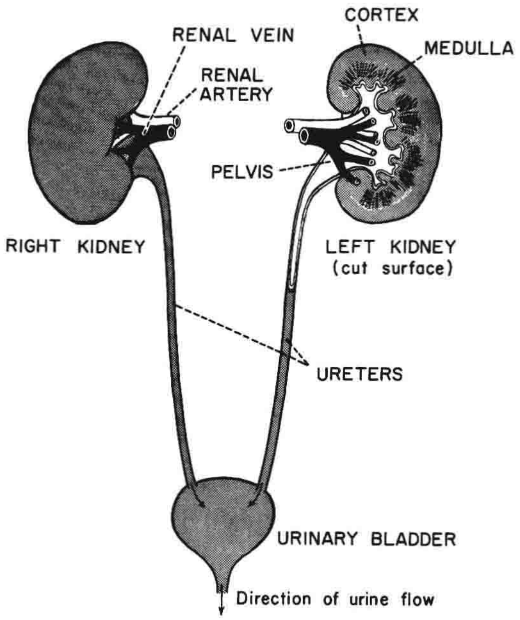

Figure 6. The kidneys and urinary system.

actions could take place. For this reason it is important that the kidneys remove these unwanted substances.

The kidneys have another very valuable function besides that of excretion: they regulate the concentration of most of the electrolytes in the body fluids. A very large proportion of these electrolytes is sodium chloride or common table salt. The kidneys continually adjust the concentrations of both sodium and chloride, and they also regulate very precisely the concentrations of potassium, magnesium, phosphates, and many other substances. The kidneys perform this function by allowing the unwanted substances such as urea to pass easily into the urine while retaining the wanted substances such as glucose. If sodium is already present in the blood in too large a concentration, it becomes an unwanted substance, and much of it is excreted by the kidneys. However, if the concentration of sodium is too low, it is a wanted substance instead, and the kidney's special properties, which will be described in a future chapter, then prevent its loss from the blood.

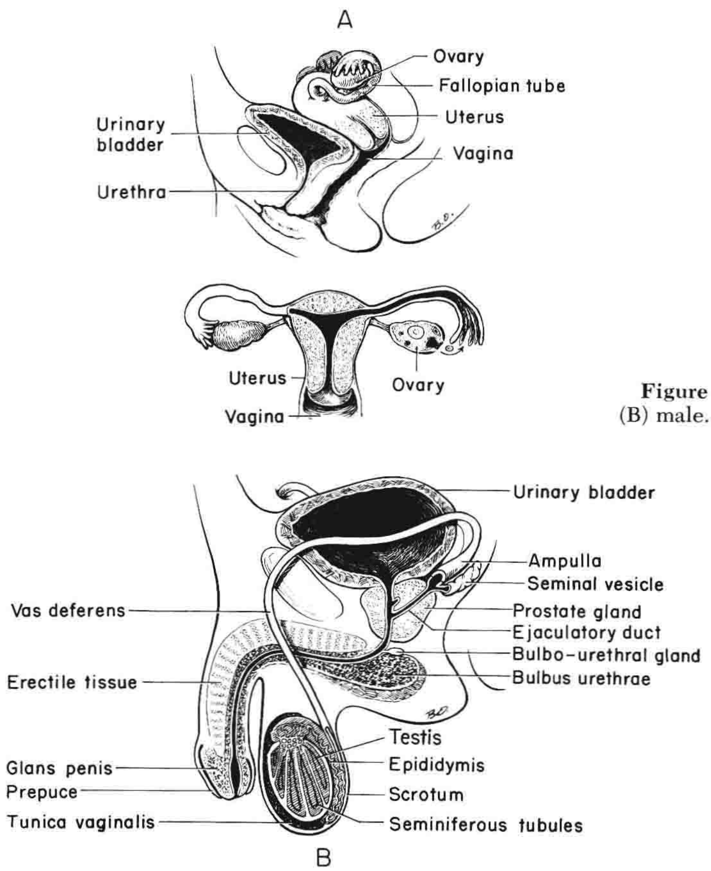

Figure 7. The reproductive systems: (A) female, (B) male.