Guyton

Physiology of the Human Body

SIXTH EDITION

PHYSIOLOGY OF THE HUMAN BODY

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Preface

My purpose in writing this book has been to present the basic philosophy of human function, with the hope that I might pass on to others my own love for the intrinsic functional beauty that underlies life itself. I have tried to present the human being as a thinking, sensing, active creature capable of living almost automatically and yet also capable of immense diversity of function that characterizes higher forms of life. There is no machine yet devised, or ever to be devised, that has more excitement or more majesty than the human body. Therefore, I hope that the reader will learn with pleasure and enthusiasm how his body functions.

Because the field of human physiology is very extensive, the character of a book in this field is necessarily determined by the choice of material that is presented. In this text a special attempt has been made to choose those aspects of human physiology that will lead the reader to an understanding of basic principles and concepts. Yet, because portions of human physiology are still only partly understood, a strong effort has been made to distinguish fact from theory, but not to burden the reader with intricate and insignificant details that more properly belong in a reference textbook.

This textbook has been published in five previous editions, the first four under the title *Function of the Human Body* and the fifth under the title *Physiology of the Human Body*. The change in title was made simply to indicate that the text is used widely, as was intended, in physiology courses in a variety of schools throughout the world.

In this sixth edition, the text has been revised extensively, mainly because physiology continues in a dynamic stage of discovery, with new knowledge of basic physiological concepts generated each day. Among the most rapidly developing areas of physiology in the past few years have been, first, the molecular basis of cellular mechanisms—especially the relationship of the genes to cell function—and, second, the interrelationships between cell function and function of the overall organ complex of the body.

Aside from the text revision, essentially all of the figures also have been redrawn in new two-color formats that we believe will be most suitable for emphasizing basic physiological concepts, this in addition to the aesthetic value of the color.

A text such as this requires work by many different people, not the least of whom are the teachers who send suggestions to the

author. Feedback of this type has helped immensely in making the earlier editions progressively better and I hope also in making this Sixth Edition still much better as well. I wish also to express my appreciation to Mrs. Laveda Morgan, Ms. Gwendolyn Robbins, and Mrs. Elaine Steed-Davis for their superb secretarial help in preparing this edition, to Ms. Tomika Mita for her renditions of most of the original figures, and to the staff of Saunders College Publishing for their continued excellence in production of this book, especially to Mr. Michael Brown and Mr. Lloyd Black for their editorial contributions and to J & R Technical Services for its extensive work in developing the new color renditions of the figures.

Arthur C. Guyton

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Introduction

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Introduction to Human Physiology

Overview

The word *physiology* means the science of function in living organisms, and study of this subject goes a long way toward explaining life itself.

The basic functional unit of the body is the *cell*, of which there are about 75 trillion in each human being. Most cells are alive, and most can also reproduce and thereby sustain the continuum of life.

Extracellular fluid fills the spaces between the cells. This fluid is called the *internal environment* of the body—it is in this environment that the cells live. The extracellular fluid contains the nutrients and other constituents necessary for maintenance of cellular life. The functions of most of the organs of the body are geared toward maintaining constant physical conditions and concentrations of dissolved substances in this internal environment. This condition of constancy in the internal environment is called *homeostasis*.

The fluid of the internal environment is mixed constantly throughout the body by (1) pumping of blood through the circulatory system by the heart and (2) diffusion of fluid both outward and inward through the capillary membranes to allow exchange between that portion of the extracellular fluid in the blood called the *plasma* and that portion in the spaces between the tissue cells called the *interstitial fluid*.

Each organ system of the body plays its specific role in homeostasis. For instance, the **respiratory system** controls both the oxygen and the carbon dioxide concentrations in the internal environment. The kidneys remove waste products from the body fluids while also controlling the concentrations of the different ions. The **digestive system** processes the food to provide appropriate nutrients for the internal environment. The **muscles** and the **skeleton** provide support and locomotion for the body, so that it can seek out its needs, especially those of providing the necessary food and drink for the internal environment. The **nervous system** innervates the muscles and also controls the functions of many of the internal organs, and it functions in association with the respiratory system to control the concentrations of carbon dioxide and oxygen. The **endocrine system** controls most of the metabolic functions of the body, including the rates of cellular chemical reactions; the concentrations of glucose, fats, and amino acids in the body fluids; and the synthesis of new substances needed by the cells. Even the **reproductive system** plays a role in homeostasis because it provides for new human beings and therefore new internal environments as the old ones age and die.

What Is Physiology? We could spend the remainder of our lives attempting to define the word "physiology," 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? How do fish obtain oxygen from the sea and in what way do they utilize it once they have obtained it? How is food digested? And what is the nature of the thinking process in the brain?

Even small viruses weighing one millionth of a single bacterium 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 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 the vast discipline of physiology.

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 needed for exercise and other types of bodily activity, and 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

The basic functional unit of the body is the cell, and 75 trillion cells make up the human body. Each of these is a living organism in itself, capable of existing, performing chemical reactions, and contributing its part to the overall function of the body—also capable in most instances of reproducing itself to replenish the cells that die.

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 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 necessary 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 refer many times again to cellular function as the basis of organ and system operation.

The Internal Environment and Homeostasis

All cells of the body live in a bath of fluid, fluid that weaves its way through the minute spaces between the cells, that moves in and out of the blood vessels, and that is carried in the blood from one part of the body to another. This mass of fluid that constantly bathes the outsides of the cells is called the **extracellular fluid**.

For the cells of the body to continue living, there is one major requirement: The composition of the extracellular fluid must be controlled very exactly from moment to moment and day to day, with no single important constituent ever varying more than a few percent. Indeed, most 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 extracellular fluid. Claude Bernard, the great nineteenth-century physiologist who originated much of our modern physiologic thought, called the extracellular fluids that surround the cells the *milieu intérieur*, 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, that is, the constancy of the extracellular fluid? 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; and water and dissolved substances diffuse back and forth between the blood and the fluids that surround the cells. Thus, the circulatory system keeps the extracellular fluid in all parts of the body constantly mixed with one another. 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 fluid 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 fluids 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 that 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 or the human being 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 sustained life of the cells depends on maintenance of an appropriate environment in the extracellular fluids. In turn, the organs and the cells, in their own ways, play individual roles in maintaining constancy of this internal fluid environment, the process that we call homeostasis.

ORGANS AND SYSTEMS OF THE HUMAN BODY

For those students who have not yet learned the basic structure of the human body, we need now to retreat for a few moments and review its major functional components.

The Skeleton and its Attached Muscles

Figure 1–1 illustrates the skeleton with some of its attached muscles. 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

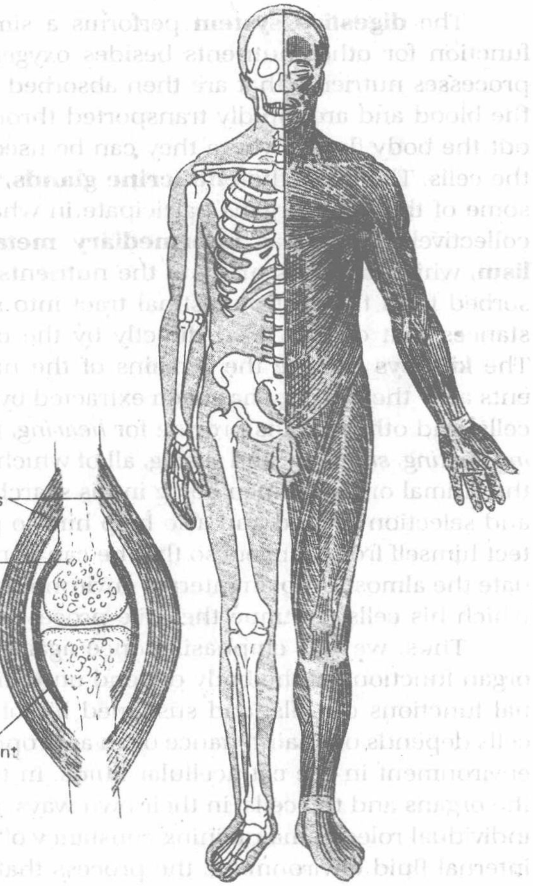

FIGURE 1–1 The skeletal and muscular systems of the human body.

is a thick, slippery fluid containing hyaluronic acid, a mucus-like substance that 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 joints, particularly those of the 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 functions on the front and several muscles on the back of the joint. There is a similar arrangement of muscles anteriorly and posteriorly about the ankle, except that the ligaments of the ankle allow the ankle joint 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 100 different individual muscles each one of which performs a specific function: One rotates an adjacent vertebra, a second flexes the vertebra laterally, a third extends it backward, and so on. This is analogous to the arrangement of the centipede, for each segment can bend independently of all the others. The joints connecting the head to the spinal column are supplied with many additional 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 a frame of bones that 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 mainly in one direction, the ankle joint in two, and the hip joint in two directions plus an additional rotary motion; and, in general, at least two opposing muscles are available for each motion that the ligaments of a joint allow.

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 joints so that any pull exerted will effect appropriate movement.

All muscles are not exactly alike in size and appearance; for instance, the smallest skeleton muscle of the body, the stapedius, is a minute muscle in the middle ear only a few millimeters long, whereas the longest muscle, the sartorius, extends almost two thirds of a meter down the entire length of the thigh, connecting from the bony pelvis all the way down to the tibia, below the knee. Some muscles, such as those of the abdominal wall, are arranged in thin sheets; others are round, cigar-shaped structures, for example, the biceps, which lifts the forearm, and the gastrocnemius, which flexes the foot downward 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. This will be discussed in detail in Chapter 7.

The Nervous System

The nervous system, illustrated in Figure 1–2, 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. Therefore, 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 and inside the body, and the **motor portion,** which controls the muscles and glandular secretion.

The sensory portion operates through the senses of sight, hearing, smell, taste, and feeling. The sense of feeling is actually many different senses, for one can feel light touch, pinpricks, 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,

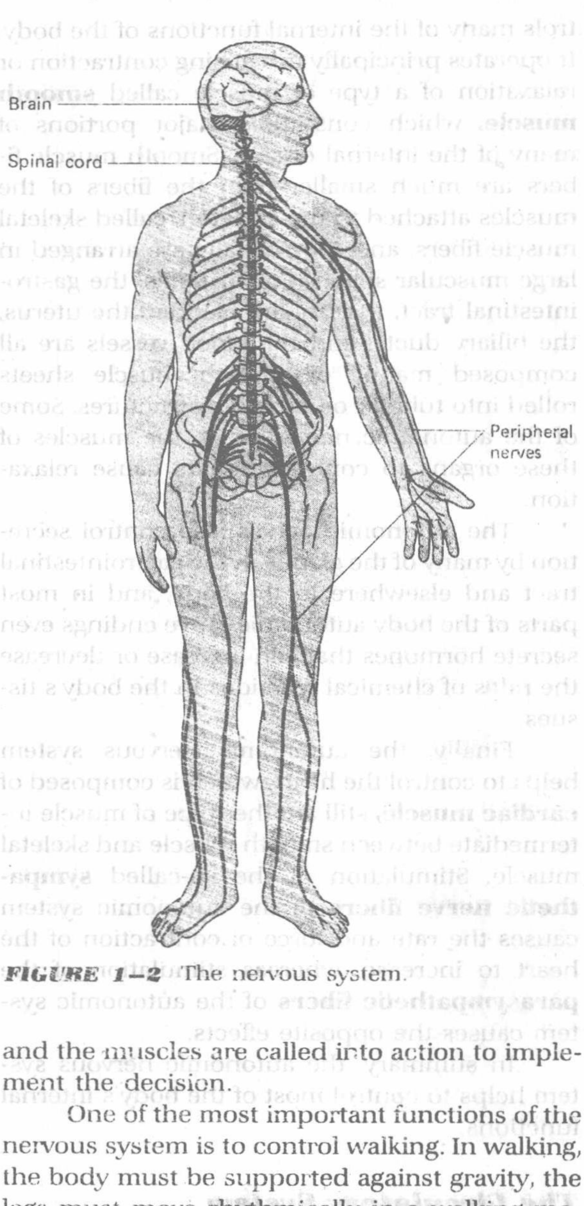

FIGURE 1–2 The nervous system.

and the muscles are called into action to implement the decision.

One of the most important functions of the nervous system is to control 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, controls 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 the fibers of the muscles attached to the skeleton, called 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; others cause relaxation.

The autonomic nerves also control secretion by many of the glands in the gastrointestinal tract and elsewhere in the body, and in most parts of the body autonomic 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,** still another type of muscle intermediate between smooth muscle and skeletal muscle. Stimulation of the so-called **sympathetic nerve fibers** of the autonomic system causes the rate and force of contraction of the heart to increase, whereas stimulation of the **parasympathetic fibers** of the autonomic system causes the opposite effects.

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 1–3, is composed mainly of the heart and blood vessels. The **heart** consists of two separate pumps arranged side by side. The first pumps blood into the lungs. From here, the blood returns to the second pump to be pumped then into the **systemic arteries,** which transport it through the body. From the arteries it flows into the

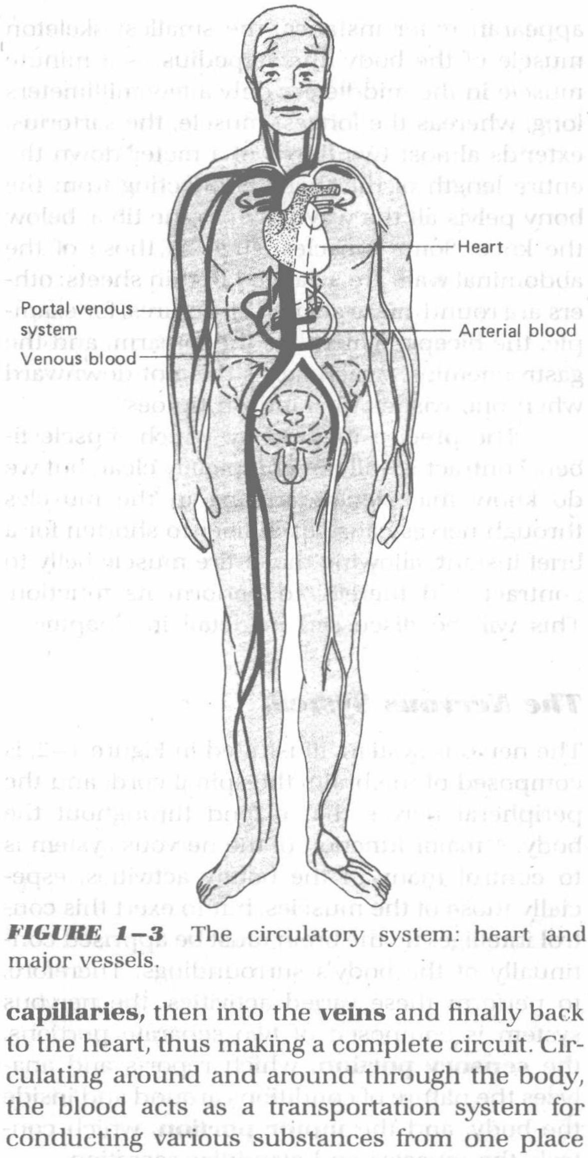

FIGURE 1–3 The circulatory system: heart and major vessels.

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 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.

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

The Lymphatic System. Large particles that appear for any reason in the tissue spaces, such as old debris of dead tissues, protein molecules, and dead bacteria, cannot pass from the tissues through the small pores of the blood capillaries. A special accessory circulatory system known as the **lymphatic system** takes care of these materials. Lymph vessels originate in small **lymph capillaries,** which lie beside the blood capillaries. And **lymph,** which is fluid derived from the spaces between the cells, flows along the lymph vessels up to the neck where these vessels empty into the neck veins. The lymph capillaries are extremely porous so that large particles can enter the lymph vessels and be transported by the lymph. At several points along the course of the lymph vessels, the lymph passes 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 1–4 illustrates 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 other nutrients from foods to release energy. This energy, 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 the cells.

When oxygen combines with the food nutrients to liberate energy, carbon dioxide is formed. This diffuses through the tissue fluids into the blood and is then carried by the blood

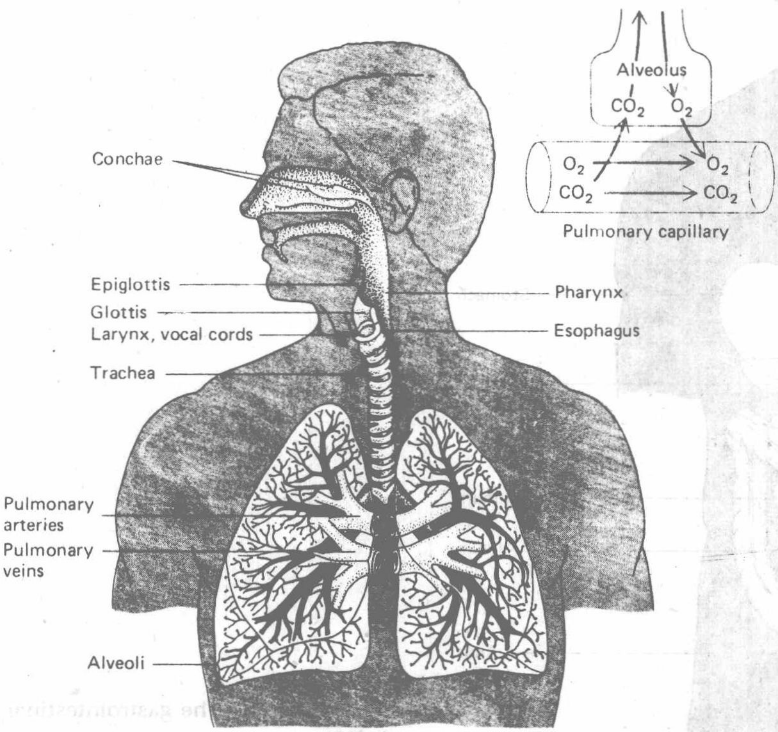

FIGURE 1–4 The respiratory system.