MECHANISMS OF BODY FUNCTIONS

by Dexter M. Easton

Preface

This book is intended as a general introduction to human physiology for the student who has had little or no training in the biological and physical sciences at the college level. Since physiology is founded on physics, chemistry, and anatomy, the elementary concepts of these sciences are discussed when they are necessary to clarify the physiological principles. Since physiology is partly a quantitative science, a few simple examples of physiological measurements are provided. In most instances, the anatomical descriptions are functional in approach and serve as a background for the discussions of physiological mechanisms. If there is a special emphasis in this book, it is on the role of the nervous system in regulating the diverse functions of the body machinery.

A large part of the text is necessarily concerned with simple word descriptions of functional aspects of human biology. The student will probably encounter some unfamiliar words, as well as familiar words used in unfamiliar ways. He should not hesitate to use a dictionary when reading these pages.

The sequence in which the physiological topics are treated is a logical one, preferred by many teachers. The general field and methods of physiological thought, particularly in terms of cells, are mentioned in the introductory chapter. Thereafter, the topics are arranged in an organ system sequence: skeletal, muscle, and nervous systems occupy the first half of the book. The autonomic nervous system provides a transition to the discussion of adjustments controlled by the hormones carried in the circulation. Then follow particular contributions made by muscle, nerve, hormones, and circulatory system to the major body functions of respiration, digestion, metabolism, excretion, and reproduction. The circle is completed in the final chapter with a discussion of the physiology of heredity, which brings us back to the cell.

The illustrations have been drawn specifically to illustrate the text material. Careful attention should be paid to them and to their legends. In some instances, these legends serve as summaries of portions of the text. The figures have been synthesized from many sources, original, published, and unpublished. The final rendering of most of the figures was performed by Mr. Spence Guerin; a few were finished by Mr. Vann Elliot Smith. I am grateful to the several individuals and publishers who made available the photographs used for the half-tone illustrations heading each chapter.

Special thanks are due to several of my colleagues whose critical comments about statements of presumed facts and about matters of style have helped me to improve the several drafts of the manuscript. I am especially grateful to Dr. Harry J. Lipner for his detailed and pointed criticisms. I am indebted to Dr. Lloyd M. Beidler, Dr. Howard D. Baker, and Dr. Charles W. Edington for their comments on separate sections and chapters. My wife, Jean, was most helpful in matters of grammar and sentence structure. In addition, her general criticisms as a non-scientist helped me to clarify and simplify several portions of the text.

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Contents

1

Physiology and the properties of life

Human physiology is part of the study of life

Life on earth depends upon the sun. The green chlorophyll of plants captures the energy of sunlight and locks it into chemical compounds that provide fuel to keep the plants alive. Animals that eat the plants use the same fuel to keep themslves functioning. The explanations of how these events take place in living things—from absorption of sunlight by plants to the motions of animals—all lie within the science of physiology. Like any other animal, the human being is a kind of machine, for a machine is a "... device ... which may serve to transmit and modify force or motion so as to do some desired kind of work."[1] Human physiology is the study of how our own body machinery functions.

The many kinds of living things on our planet appear superficially very different from one another but are alike in many ways. Of the more than one hundred chemical elements in the universe, less than twenty—and these the smaller atoms—make up the main substance of living things. Every living thing is remarkably similar to every other in the proportions of these elements.

Four small atoms, hydrogen (H), carbon (C), oxygen (O), and nitrogen (N), provide the structure of about 95 per cent of any animal or plant. These atoms are attached together to form overwhelmingly complex molecules that are remarkable because of their organization into arrangements that can duplicate themselves. This characteristic is so outstanding that it provides a definition of living things: *Living things are chemical machines that grow, replace their own worn-out parts, and reproduce themselves.*

We would expect machines with self-replacement and reproductive abilities to be complicated, and, indeed, a multitude of chemical changes—collectively described as *metabolism*—go on in living things. *Assimilation*, *irritability*, and *motility* are other important characteristics of living things. Assimilation involves ingestion and absorption of food to provide the raw materials for energy and structure; irritability refers to the ability to detect environmental changes and make appropriate adjustments to these changes. Most cells at some

[1] *Webster's New Collegiate Dictionary* (Springfield, Mass.: G. & C. Merriam Co., Publishers, 1961). A dictionary is an indispensable aid to the beginner in physiology.

time during their lives are motile, that is, they move in one manner or another.

The unit of life is the cell

The chemical machinery of any living thing is arranged in small packets called *cells*. In biology, the name *cell* was originally given to the microscopic structures seen in a slice of cork. These chambers are, however, only the dead cellulose walls that have been manufactured by the living structure of the bark of the cork tree. The term now is used to mean the smallest part into which a living thing may be divided and still show the properties of life. Some animals and plants consist of only one cell. This cell can assimilate and metabolize food; it responds to its environment and is capable of reproduction, usually in conjunction with another cell.

Although cells are generally considered to be the most elementary forms of life, viruses (which are smaller) are sometimes described as the simplest living things. Actually, viruses are incomplete forms of life, parasitic on cells. The virus molecule isolated from a cell has no more life than a crystal of table salt. A virus must be inside a cell to function. In the presence of a virus specific to it, part of the metabolic machinery of the cell is shifted to manufacture virus, rather than normal cell substance. Virus particles outside the kind of cell in which they are parasitic cannot reproduce themselves.

Cells vary in size and shape. A fertilized egg, such as that from which each of us began, is a sphere about 100 μ (0.1 mm or about 0.004 in.) in diameter, barely visible to the unaided eye.[2] The nerve cells that signal a touch of the finger tips are fibers longer than the arm and thinner than the finest hair.

A living cell is bounded by a *membrane* that holds the cellular contents together and prevents the cell substance from dissolving into the watery environment. The membrane itself is part of the living substance, but it may be surrounded by nonliving walls, such as the cellulose walls around plant cells, or the material of bone that encloses bone cells.

The chemical substances of which a cell is constructed are collectively called *protoplasm*. This term includes the cell membrane

[2] μ is a Greek letter equivalent to the English *m*. It is used in measurement to symbolize the *micron* which is equal to 1/1000 mm. Thus 100 μ means *"100 microns."*

but excludes material that may be merely stored as droplets or crystals within the cell. Protoplasm, the "primary living stuff," is a complicated but precisely organized collection of chemical materials. It is essentially a water solution of certain special organic and inorganic salts and nonelectrolytes. It is a very special kind of solution reminding one of a jelly. A spoonful of gelatin (a protein) in hot water makes a rather ordinary-looking solution. Allowed to cool, it becomes a semi-hardened mass in which the water is held in the interstices of a loose gelatin meshwork. In an analogous way, the protein in protoplasm provides a sort of meshwork holding tremendous amounts of water. Unlike the homogeneous jelly, the protoplasm of a cell contains definite, microscopic structures (Fig. 1-1).

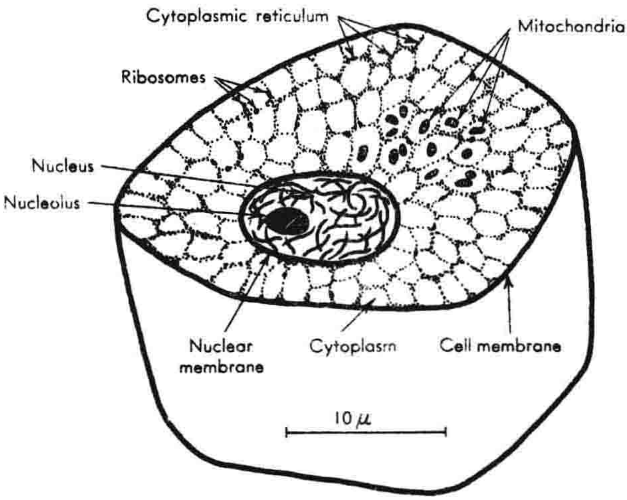

Fig. 1-1. Diagram of a generalized cell. The cytoplasmic reticulum appears to be a system of canals pervading the cytoplasm. The ribosomes are small particles on it; the mitochondria are in the spaces between the canals.

The *nucleus* is the largest separate structure and is most important for continued life of the cell. The protoplasm within the *nuclear membrane* is called *nucleoplasm* to distinguish it from the surrounding *cytoplasm*. The nucleus renews the chemical machinery of the cytoplasm. In its absence, the cytoplasm can function only a limited time. If the nucleus is experimentally removed from a cell, the cell will usually live only a few days. Yet in our own bodies, the red blood cells normally lose their nuclei before they are released into the circulation. These cells live as long as one hundred and twenty days.

The nucleus is also the part of the cell most clearly capable of self-reproduction. By manufacturing replicas of itself, it is responsible for the multiplication of cells. As cell division proceeds, differences that are controlled by the nucleus develop among the cells. The nucleus is responsible for reproduction of the species. Differences among individuals and among species of animals depend ultimately upon small differences in the structure of the material of the nucleus.

In the cytoplasm a large surface area is made available by the *endoplasmic reticulum,* which in many cells seems to be a tremendously folded and crumpled membrane that may be a continuous infolding of the cell membrane. Associated with the reticulum are tiny spherical particles called *ribosomes,* which are about 100 mμ [3] in diameter. The *mitochondria* are variously shaped particles in the cytoplasm outside of the reticulum. They are 1 to 5 μ in greatest dimension. Within each mitochondrion, a much-folded internal structure provides a large surface area.

It is speculated that the intake of food materials into the cell may be along channels from the outside of the cell into the endoplasmic reticulum. Cellular chemical changes that occur in appropriate sequence for the work of the cell apparently are related to the ribosomes and mitochondria.

The cells may manufacture molecules that become new cells, or carry electrical charges, or produce movement. Still other molecules manufactured by the cells reach the outside of the cell membrane as *secretions.* Some secretions are carried away in the surrounding fluid, but others remain attached to the cell membrane and form part of a matrix within which the cell lives.

Cellular differentiation

In single-celled animals, all the functions of life are adequately carried out in one cell. In multicellular organisms, groups of cells become specialized in their functions; that is, certain cells carry on one or more of the functions of life more effectively than others. For example, nerve cells carrying impulses specialize in irritability, but muscle cells exert force, thus providing motility. Such specialized cells are said to be *differentiated;* that is, they have become different from other cells. The fertilized egg from which we begin is *un*differentiated. During the course of cell division, groups of cells appear

[3] Lower case m preceding the symbol μ indicates division by 1000. Therefore one mμ ("millimicron") is 0.001 μ.

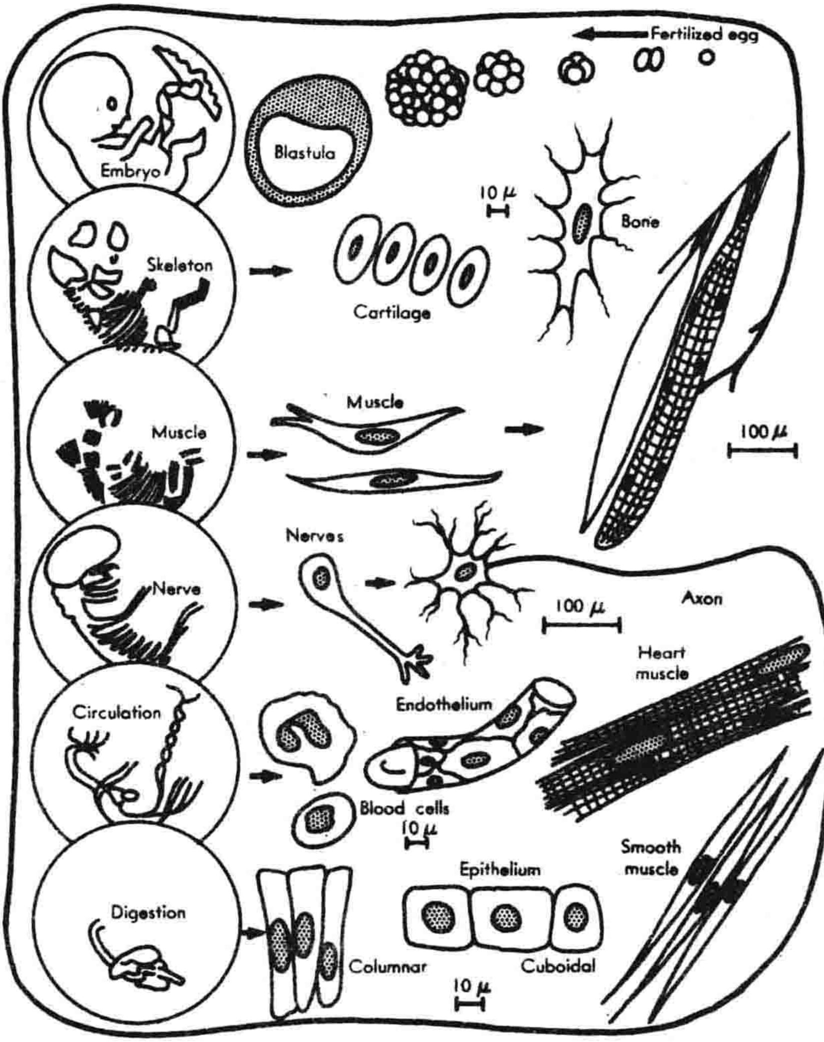

Fig. 1-2. Cells differentiated from a fertilized egg. Only some of the organ systems and cell types are shown. The digestive and respiratory systems are nonfunctional in the embryo. Comparative sizes to an order of magnitude are suggested by the scales.

that are unlike their neighbors (Fig. 1-2).[4] In general, the cells that are present early in the development of an individual are relatively undifferentiated; similarly, young cells of an individual are relatively undifferentiated compared with older cells of the same individual.

The circumstances giving rise to differentiation are little under-

[4] The mechanisms of cell division are described in detail in Chapter 11.

stood. The nucleus, which controls the life of a cell, is generally assumed to be the same from one generation of cells to the next. The constituents of the cytoplasm may become altered, however. Changes in the course of cytoplasmic chemical processes that follow such alterations may give rise to what we see as functional and anatomical differentiation of the cells.

Specialization of function by cells is generally accompanied by relative loss of other functions. For example, many cells lose the ability to reproduce, following differentiation. There is no multiplication of nerve cells or muscle cells after a relatively young age, although these cells continue to grow by increasing in size.

Some types of cells continue to multiply even in the older individual. This is true of certain cells of the skin, of the reproductive system, and of other cells that line the digestive tract. In continually growing tissues of this sort, the finally differentiated cells do not, however, reproduce. It may not, then, always be possible to demonstrate in any particular cell all of the functions that living things are supposed to show. It may be necessary to look into the history of the cell to find a time when some of these features were present.

Cells will occasionally regain the lost ability to reproduce. They lose their differentiated condition and begin to grow and reproduce in an unorganized and uncontrolled fashion. The various cancers are examples of this condition.

The environment of cells

For a free-living cell, the environment is the entire watery world in which it lives. The cells of the body also have access to a fluid environment, but they have other cells as close neighbors. When these cells are of like kind, the entire assemblage of similar cells is called a *tissue*. The fluid in direct contact with the cells fills the *intercellular* (or *tissue*) *spaces* among the cells and is called *tissue fluid*. The volume occupied by fluid is small compared with the dimensions of the cells. The fluid, moving slowly through the intercellular spaces, forms a continuous aqueous environment for all the cells. This is the *internal environment* of the body.

The composition of the tissue fluid depends upon what the cells secrete into it and what it receives from the blood. Although the blood flows in closed vessels and is thus separated from the fluid in the tissue spaces, certain substances can move through the permeable walls of these vessels. The internal environment is therefore, in effect, continuous with the blood stream which flows in the tiny capillaries near all the body cells. Substances in the aqueous medium move continually from blood to tissue fluid and from tissue fluid to blood. By means of this exchange the internal environment is kept uniform and constant in its properties. Constancy of temperature, of salt concentration, of food materials, and of oxygen are all necessary if the cells are to function as they should.

The condition of stability of the internal environment is called *homeostasis*. Homeostasis is maintained by a multitude of small adjustments in such variables as secretory activity, muscle contraction, and blood flow. These adjustments are made in response to any influence on the body that tends to upset the balance of body functions.

The numerous homeostatic mechanisms of the body resemble certain man-made devices. By means of a thermostat, for example, a heating or cooling device compensates for loss or gain of heat by the building in which it is installed and thus keeps the temperature of the building constant. The temperature of the body must also be kept constant in the face of great fluctuations in the outside world. In the thermostatic machinery of the body or of the building, a small departure from a prearranged level serves as a signal to reverse the change.

Varieties of tissues

Most cells of the body remain relatively fixed in position. Tissues made up of flat sheets of cells cover the surface of the body to form the skin; they also line the inner and outer surface of such structures as the lungs and digestive tract. Such tissues are called *epithelia.* The cells of an epithelium are arranged side by side and are held together by an *intercellular cement.* They have access to the fluid environment at their free sides. Forming continuous sheets in this fashion, epithelia may control passage of materials in and out of the larger tissue spaces.

Protection at the skin surface is afforded by the rapidly proliferating layers of the *stratified squamous epithelium,* which consists of overlapping layers of flat cells (Fig. 1-2). Passage of oxygen into the blood, and of carbon dioxide out, is permitted by the thin, singlelayered *simple squamous epithelium* that lines the final subdivisions of the lungs. A similar thin layer lining the blood vessels permits selective passage of materials from the blood stream into the tissue spaces, thus allowing the cells to receive nutrients. The layer of cells, in this instance being *within* the body, is called an *endothelium.*

At surfaces where there is active secretion from one side to the other, tall, column-like cells form a *columnar epithelium.* Such tissue is found, for example, along the excretory tubules of the kidney, and along the digestive tract, which is lined by *stratified* (that is, multi-layered) *columnar epithelium.* A special *ciliated columnar epithelium* lines parts of the lungs. The whip-like *cilia* in these cells assist in moving undesirable particles out of the lungs.

Connective tissues of various kinds help hold all the other tissues together, as the name *connective* implies. There is very little extracellular material between the cells of an epithelium, but the cells of many types of connective tissue are surrounded by an obvious matrix of material secreted by the cells.

Adipose connective tissue cells store fats in their cytoplasm, but *fibrous connective tissue* cells secrete tough materials to provide tendons and ligaments. *Cartilage* cells secrete a tough waxy material that in many instances is a precursor to *bone,* a special hard connective tissue that provides the frame for the entire body. Blood is also a connective tissue. It differs from other connective tissues in that the cells are not fixed in position, but are carried about in the fluid part of the blood.

Nervous tissue is composed of nerve cells having long extensions that, distributed among all the tissues of the body, carry messages throughout the body. *Neuroglial cells* serve as a kind of connective tissue among the nerve cells. Some of them pour secretions into the blood stream. Others provide nourishment to nerve cells.

The most obvious *muscle tissue* is *skeletal muscle,* but *smooth muscle* can be discovered in all blood vessels, in the digestive tract, in the excretory, and in the reproductive systems. Heart muscle cells differ from those of either skeletal or smooth muscle.

Organs and systems

In complicated animals such as ourselves, *organs* are formed of various combinations and proportions of several tissues such as *muscle* for movement, *nerve* for impulse conduction, and *connective* for holding the structure together (Fig. 1-2). The brain, stomach, and heart are organs. The brain is mostly nerve tissue, but there is muscle tissue in its blood vessels. Stomach and heart are mostly muscle, supplied with a rich network of nerves. The organs, in turn, are assembled into *body systems*—each of which is especially suited to a particular function. Body systems, organs, and tissues concerned with physiological functions are listed in the accompanying table.

The *skin*, the *respiratory system*, the *excretory system*, and the *digestive system* control the passage of certain substances into and out of the body. The *skeletal system* provides support; the *muscle system* moves the parts of the body. The *nervous system* carries in-

ANATOMICAL AND PHYSIOLOGICAL RELATIONSHIPS

Anatomical system	Physiological function	Typical organs	Microscopic constituents, tissues
Skeletal	Support (cells secrete tough matrix)	Bone	Bone cells
Muscular	Movement (contraction)	Muscle	Muscle cells
Nervous	Detection and transfer of information (irritability)	Brain Spinal cord Eye Ear	Nerve cells Neuroglia
Circulatory	Movement of fluid environment	Heart Blood vessels Capillaries	Endothelium Heart muscle Smooth muscle Connective tissue
Respiratory	Gas exchange	Lungs	Epithelium Nerve Smooth muscle
Digestive	Digestion of food (absorption, secretion)	Stomach Liver Intestine	Epithelium Nerve Smooth muscle
Excretory	Removal of wastes, secretion, filtration	Kidneys	Epithelium
Endocrine	Chemical integration of body functions Secretion	Pituitary Thyroid Adrenal	Epithelial origin Connective tissue
Reproductive	Reproduction Cell division	Testis Ovary	Epithelial origin