ELEMENTS OF BIOPHYSICS

by

JAMES E. RANDALL, B.S.E.E., M.S., Ph.D.

Associate Professor of Physiology and Biophysics
Department of Physiology and Pharmacology
University of Missouri Medical Center

THE YEAR BOOK PUBLISHERS • INC.

200 EAST ILLINOIS STREET • CHICAGO

PRINTED IN U.S.A.

Preface

A UNIVERSALLY ACCEPTABLE DEFINITION of biophysics appears to be an impossibility at this writing. Of course in its broadest sense the term signifies the union of the physical and the life sciences, but such a generalization carries little clarifying information. It is important for the reader of this book to understand that this text was not undertaken in an attempt to define what should be considered as biophysics, but rather as an effort to present to the student of biology and medicine the physical and quantitative concepts of basic importance to these fields.

If the current literature and research activities can be taken as an index, this is truly an era in which physical concepts play a fundamental role in biological and medical experimentation and comprehension. It is the thought of many that physical ideas oriented in biological situations deserve more attention in the biologists' training. Such physical mechanisms and physical properties are of importance at all levels of biological function. It is very probable that the full understanding of some of the most interesting biological mechanisms—as, for example, the specificity of hormone and antigen-antibody reactions—can only be understood by considering both the chemical and the physical actions operating at the molecular level. However, for didactic reasons, I have chosen the illustrations for the concepts presented herein from the systems level of biology because actions at this level are more easily perceived by the student. The concepts are introduced within a sufficiently broad framework that they can be applied, in most cases, to biology generally.

In giving this material with breadth it has been necessary to limit the (often frightening) rigorously quantitative and analytical contributions that biophysics can make. But it is hoped that this text will provide for the student a stepping stone between his undergraduate physics and the current physical interest in biology and medicine.

This text has developed from a 32-lecture course in biophysics given by the author at the University of Missouri Medical Center. The students in the course consist of the members of the freshman medical class and graduate students from the biological sciences, all of whom have had one year of college physics and at least algebra. The first four chapters of the book introduce certain aspects of the quantitation process which are important in current medical thinking but which are not usually experienced in a student's background. This section begins by pointing out the inherent simplicity of quantitation which results from defining all physical quantities in terms of mass, length, and time. Also several mathematical operations upon quantities are illustrated in physiological terms, including integration, differentiation, exponential rate phenomena, and frequency analysis. The features of measurements and instrumentation, the practical means of obtaining quantities, are included, with stress on the limitations imposed by biological material. The chapter on statistics summarizes many of the basic ideas which must be understood in order to quantitate and assess the significance of magnitudes which are subject to the variabilities so characteristic of biology.

Chapters 5–10 are concerned with creating an integrated picture of the forces and energies associated with masses, electric charges, and electromagnetism. The illustrations stress the broader aspect of these concepts, with the thought that deeper meaning will be obtained by the student in courses that are integrated with respect to organisms rather than with respect to physical ideas.

The nuclear radiations are utilized by this generation of scientists and clinicians as vital research tools and as modalities for applying energy; and so, in the balance of the book, the important aspects of nuclear energy are defined and illustrated for the biologist.

In a text which is primarily concerned with the presentation and organization of basic concepts, as this book is, it is difficult for the author to give proper credit to the source of much of the material, for, in reality, the book is a reflection of his entire education process. I would therefore like to acknowledge the anonymous educators and authors who have contributed to this text by their skill in teaching. At the same time, I wish to assume the responsibility for any errors which may be contained herein.

Fortunately, there are a number of persons whose contributions I can acknowledge in a less vague fashion. Professor B. A. Westfall was most encouraging in the manner in which he supplied the facilities and the time of his department. Professor Dallas K. Meyer was very helpful during the time in which the local biophysics course was being organized. I am indebted to Professor Sir Ronald A. Fisher, of Cambridge, to Dr. Frank Yates, of Rothamsted, and to Messrs. Oliver & Boyd, Ltd., of Edinburgh, for permission to reprint Tables 4.2, 4.3, and 4.7 from *Statistical Tables for Biological, Agricultural, and Medical Research* (1949). The manuscript typing has been capably handled, at various phases of the project, by Loretta Petrich, Delores Koftan, and Delores Crockett. Edward Jackson and Ernest Miles have prepared the illustrations, with obvious skill. Also, the author's wife, Barbara, has been of great assistance in the preparation of the manuscript.

JAMES E. RANDALL

Table of Contents

CHAPTER 1

Quantitation

FUNDAMENTAL PHYSICAL QUANTITIES

ONE OF THE BASIC TENETS of scientific endeavor is that of placing the observations, the laws, and the theories upon an exact and an objective basis. In the past an individual area of science has initially gone through a descriptive phase; and then, as the science progressed, information regarding it became more quantitative. Physics is an outstanding example with such a history. It is believed by many that biology has passed through its descriptive era and that the era of quantitative biology is beginning.

The process of quantitation may consist of simply counting a number of individuals or units. An outstanding example of the success of such a simple quantitation in biology is the classic Mendelian genetics, in which the essential quantitation is the counting of phenotypes. A formal science has been derived from such quantitation, and it provides us with laws and theories by which we can predict the hereditary transmission of phenotypes.

Much material which is to be quantitated must be handled by comparison with some accepted standard. In biology this accepted standard is often a rather arbitrary and descriptive one, such as the dose of an agent needed to produce a given biological effect. This process, known as bio-assay, is the only known means by which many pharmaceutical agents can be quantitatively determined. For example, each manufactured batch of digitalis, ouabain, insulin, acetylcholine, and of many other drugs must be assayed in regard to its concentration by injecting a given dilution into some particular animal species and then observing the effects on blood sugar or blood pressure, or even on survival of the animal. In the case of digitalis, the dosage is calculated in terms of the amount of the substance which will, upon injection, kill 50% of the cats into which it is injected. Of course such procedures are inherently inaccurate; but until a more sensitive physical or chemical procedure has been determined, these methods will have to suffice.

In the case of physics the basic quantitative concepts have more rigorous definitions. It is not the purpose here to define these in the rigorous form used by professional physicists, but it should be pointed out how arbitrary the standards are and also how fundamental the three physical quantities of mass, length, and time are. These three quantities are fundamental because so many other quantities are defined in terms of mass, length, and time. In reality, the bulk of all material in this text, and in all sciences which have material things as their basis, can in one form or another be defined in terms of these quantities.

The standard of length has been arbitrarily chosen as the distance between two lines on a metal bar in Paris. Quantitation of distances is nothing more than a process of comparing the distances with the 1 meter distance on this standard. In a similar manner, the standard of mass is the mass of a metal cylinder in Paris. Quantitation of masses is a process of comparing these masses with the standard 1 kilogram mass. The standard of time has been taken from our solar system, and the second is a given fraction of a mean solar day.

It is the function of the National Bureau of Standards to maintain an accurate replica of these standards. Naturally, these fundamental standards are used only for the most important and precise calibration purposes. It is possible to send laboratory standards to the National Bureau of Standards in Washington for calibration against the Bureau's more exact standards.

In summary: the process of quantitation involves a magnitude which is simply the number of times some standard must be utilized.

DERIVED QUANTITIES

Of the great multitude of physical quantities which are derived from these fundamental mass, length, and time quantities, only a few of the ones which are more commonly used will be mentioned: velocity, acceleration, force, and pressure. While their actual mechanical nature will be left to later sections on mechanics, these derived quantities are introduced at this point to allow the student to appreciate how really unified our scientific concepts are when expressed in terms of the fundamental physical quantities. The appreciation of this unification and integration of concepts is a large step toward the understanding of all physical scientific endeavor.

1. *Velocity* is a derived quantity involving distance per unit of time, or by definition it is the rate of change of position. For our purposes the *cm/sec* is a convenient unit of velocity.

2. *Acceleration* is a derived quantity involving rate of change of velocity, by definition. The *cm/sec*^{2} is a convenient unit for this quantity.

3. *Force* is a derived quantity which is defined as an agent capable of accelerating a mass. Quantitatively the convenient unit for force is the dyne, which is the force required to give a mass of 1 gram an acceleration of 1 cm/sec^2. The gravitational attractive force of the earth upon a 1 gm mass is such as to cause it to accelerate at about 980 cm/sec^2. Thus the attractive force upon the 1 gm mass is about 980 dynes.

4. *Pressure* is a derived quantity which is defined as the force per unit area. The unit may be expressed as *dynes/cm*^{2}. In biology and medicine the more common unit of pressure is the height of a column of mercury which the pressure will support against the earth's attractive force upon the mass of the mercury. Since pressure is such a common clinical quantity, it is of interest to clarify this particular unit of pressure quantitation.

In the mercury manometer (a pressure-measuring device) the pressure to be measured exerts a force upon a tube of mercury. The tube of mercury has mass (its volume times its density) which is responsible for a gravitational attractive force between it and the earth. The column of mercury in the tube will adjust its height until the attractive force due to its mass just equals the force due to the pressure being measured.

$$\text{Gravitational attraction} = \text{Mass of Hg} \times \text{Acceleration mass would show due to gravitational force}$$

$$= \text{Tube area} \times \text{Hg height} \times \text{Hg density} \times 980 \text{ cm/sec}^2$$

Upon transposing the tube cross-sectional area term to the left side of this equation,

$$\text{Pressure being measured} = \frac{\text{Force upon Hg}}{\text{Tube area}} = \underset{\text{(Varies with pressure)}}{\text{Hg height}} \times \underset{\text{(Constant)}}{\text{Hg density} \times 980 \text{ cm/sec}^2}$$

This equation indicates that the measured pressure will be directly proportional to the height of the mercury column in the manometer, the density of the mercury, and the gravitational acceleration of 980 cm/sec^2. It should be emphasized that the pressure is independent of the cross-sectional area of the manometer tube. This fact is sometimes hard to appreciate when one sees a small experimental animal, such as a rat, having the same blood pressure as a large man. Since mercury has an unusually high density, it is the manometer fluid of choice for high pressures, such as are encountered in the arterial side of the circulatory system. In the case of lower pressures, as in the venous system or the cerebral spinal fluid, it is sometimes more convenient to express pressure in units of centimeters of water.

It should be re-emphasized that the foregoing physical quantities and essentially all other classic physical quantities can be derived from the fundamental mass, length, and time quantities.