THE BASIC PHYSICS
of
RADIATION THERAPY

Third Edition

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By

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Preface to the Third Edition

Time has a way of slipping by: it is hard to realize that thirteen years have passed since the publication of the second edition, and twenty-nine since the first.

In this, the third edition, all material has undergone rewriting, with few exceptions. In fact, the book has been almost completely rewritten.

The International System of Metric Units (SI) has been used throughout, followed in most cases by the traditional units in parentheses. One exception is continuing use of the exposure unit, R, which still has a place in the calibration of ion chambers, in diagnostic radiology, and in specification of exposure-rate constant of discrete radioactive sources. To smooth the transition from the *rad* to the SI unit *gray* which is one hundred times larger, I have adopted a common convention using the centigray since it exactly equals the rad. Similarly, the centisievert replaces the rem, these also being equal. The SI becquerel is such an extremely small unit that it is much more convenient to use the relation 1 millicurie = 37 megabecquerels.

The introductory chapters on mathematics remain with only minor modifications. The slide rule has been deleted because of its replacement by the hand-held calculator and small computer.

Kilovoltage therapy continues to be covered because it still has a place in radiotherapy of superficial lesions that can often be treated more conveniently with this modality than with an electron beam or discrete radioactive sources. Emphasis has been essentially shifted toward high-energy photon beams, especially linear-accelerator generated megavoltage x rays, which have relegated cobalt-60 units to second-place status. This is not to say that cobalt teletherapy has become obsolete, since it still can play a role in treating some head-and-neck cancers and in management of skeletal metastases.

Much attention has been given to the AAPM Task Group 21 Protocol for calibrating high-energy photon and electron beams, with an attempt to make it more comprehensible to the radiation oncologist and radiation therapist. (The latter term replaces the previous one, radiation therapy technologist, because of its rapidly-growing acceptance by the radiology community.) Attention is also paid to the C_λ method of megavoltage beam calibration.

Electron-beam therapy has been expanded to become a separate chapter because of its increasing use in sophisticated radiotherapy, and wide availability of dual-mode linacs. Included are the physical aspects of the beam itself, in addition to its generation.

The material on radioactivity and nuclear physics has been reworked to make it more relevant to radiotherapy. Brachytherapy has been extensively rewritten and updated, with inclusion of computer-generated tables of dose distribution with radium to serve as a basis for the use of artificial radioactive substitutes in intracavitary and interstitial applications.

A chapter on radiopharmaceuticals begins with basic physical principles and elements of diagnostic instrumentation, to introduce the main subject of cancer therapy by ingestion and injection of radionuclides. Although such treatment usually falls within the province of nuclear medicine, radiation oncologists and therapists should have some familiarity with the subject.

Radiobiology is admittedly important for those working in the field of radiotherapy; this chapter still presents the basic concepts in relevant detail, with minor updating. However, greater attention has been paid to its applicability in radiotherapy.

A short chapter deals with the present status of heavy-particle teletherapy and brachytherapy, the latter with californium-252.

Finally, health physics is dealt with essentially as before, but with clarification of certain concepts and use of SI units.

The author herewith expresses his gratitude to Fritz Hager, Physicist at the East Texas Cancer Center (Tyler, Texas) for his permission to use his dose distribution tables for megavoltage x-ray beams and depth dose curves for electron beams. With few exception, the isodose charts in this book were obtained by Mr. Hager and by Mrs. Lisa Palmer, RT(T), Dosimetrist, using the AECL TP-11 therapy-planning computer, and they deserve the author's appreciation. Mr. Hager was also especially helpful with the section on practical dosimetry. However, the author takes full responsibility for any errors in the text.

Illustrations have been revised and many new ones added, with the superb artistry of Mr. Howard Marlin, to whom the author is most grateful.

In conclusion, I wish to thank sincerely Mr. Payne Thomas, of Charles C Thomas, Publisher, for his patience, advice, and attention to detail during the long incubation period of this, the third edition.

JOSEPH SELMAN, M.D.

Preface to the Second Edition

As would be expected, a number of advances have taken place in the physics of radiotherapy during the thirteen-year time span between the First and Second Editions. However, none of these may be considered monumental.

One significant change has been in units and terminology—the further clarification of the concepts of radiation exposure and dosage. While this seems to have been stabilized for the time being, there is on the horizon the threat of a more scientific, but at the same time a vastly more complex International System of Units (S.I.). This has already been accepted by the Soviet Union as well as the member countries of the European Economic Community. The S.I. will be touched upon, although there is still considerable resistance to its adoption in the United States.

In this edition, emphasis has been shifted to megavoltage radiation, and rightly so. Whereas formerly kilovoltage radiation (200 to 300 kV) had been the "backbone" of irradiation therapy the advent of cobalt 60 teletherapy, followed by the linac, has all but made kilovoltage radiation obsolete except for certain limited indications. A separate section has been added to cover electron beam therapy.

Because of growing interest in radiotherapy with heavy particles (high-LET radiation), a new chapter has been introduced to deal with this modality. Special emphasis in this regard has been placed on neutron and negative pion beams. This new chapter has been deliberately placed after that on radiobiology to provide the rationale for the use of high-LET radiation.

In general, the text has been almost completely rewritten, obsolete material eliminated, some sections combined, and some chapters rearranged. Although illustrations and tables from the First Edition have been retained wherever applicable, a number have been updated and new ones added.

The chapters covering radionuclides have been reworked and made more comprehensive. The diagnostic use of radionuclides has been minimized and major attention directed to their therapeutic application.

Radiation protection in therapy, including radionuclides, has been expanded. An example of the computation of wall protective barriers has been included, for the author feels that the radiotherapist should have at least a basic understanding of how this is done, despite the fact that it is the ultimate responsibility of the radiation physicist.

In addition to the appreciative acknowledgement of the data furnished by the manufacturers of therapy equipment cited in the First Edition, the author wishes to thank Varian for kindly providing important material on their linac units through John C. Ford, Ph.D.; and to Atomic Energy of Canada, Ltd. Revision of earlier illustrations and preparation of new ones have again been admirably executed by A. Howard Marlin, for which the author is most appreciative.

Finally, many thanks are due Charles C Thomas, Publisher, in the person of Payne Thomas, for providing the opportunity and encouragement toward the realization of this Second Edition.

JOSEPH SELMAN, M.D.

Preface to the First Edition

Physics has played a dominant role not only in the birth and development of Therapeutic Radiology, but also in the charting of its future course. Every major advance in the technical aspects of radiation therapy has been predicated on new information in physics and engineering. This is evidenced particularly by the advent and popularization of supervoltage therapy and medical radioisotopes.

To the resident in radiology, physics often looms as a major obstacle in a varied and intensive program. So often, the newcomer to radiology is keenly aware of his deficient background in the physical sciences, making his task even more difficult. Yet, a secure foundation in radiologic physics is necessary both as a part of any successful training program and as a basis upon which to build future knowledge. The chore of keeping abreast of new developments in therapy methods and apparatus, and of appraising their value, is facilitated when the radiologist is adequately trained in physics. However, there is no consensus among teachers of radiology as to the amount of time that should be devoted to physics in the average residency training program. While some believe that there is already too much emphasis on the physical basis of radiotherapy, others are of the opinion that in many cases this is being grossly neglected. Despite this difference of opinion, there can be no question that the better the radiologist's training in physics, the more intelligently he can plan his therapy and the more satisfactory will be his relationship with his consulting physicist.

The purpose of this book is to explain the fundamental physical principles underlying radiation therapy in as comprehensive and comprehensible a manner as possible, without sacrificing accuracy for simplicity. Wherever possible, the material is presented from the standpoint of the radiologist who, from his own experience, is aware of the problems confronting the resident in radiology. It is hoped that such a presentation will be of benefit not only to the resident but also as a refresher course for the practicing radiologist. Furthermore, in view of the present trend toward two-year courses in schools of x-ray technology, this book may serve to direct more attention to the physics of radiation therapy in the x-ray technician's training program. To facilitate adaptation to various curricula, the chapters and sections are so arranged that certain material can be excluded without jeopardizing the continuity of the text. For this reason, a minimum of cross references has been used; each section has been made as complete as possible in its own right.

Since experienced teachers are well aware of the shortcomings of most neophytes where mathematics is concerned, the first chapter is devoted to the mathematical concepts pertinent to Therapeutic Radiology. Matter, energy, and radiations are then covered in survey fashion in order to acquaint the student with modern "pure" physics in preparation for the more specific aspects of radiation therapy physics. The production and properties of orthovoltage x-rays are reviewed briefly, since most students will have had a certain amount of instruction along these lines. The greatest emphasis is placed on the interactions of radiation with matter, radiation dosage and quality, therapy planning, supervoltage and telecurietherapy, radioactivity and nuclear physics, and radium and radioisotope therapy. Finally, detailed consideration is given to radiobiology and health physics since these are assuming a position of ever-increasing importance not only in medicine, but in the world at large.

The Bibliography has been assembled at the end of the book in order to facilitate the location of references. A supplementary list of textbooks and other books for collateral reading has been added to broaden the scope of the student's background.

The kindness and interest of the following physicists, who reviewed portions of the manuscript and offered valuable suggestions, is acknowledged with sincere appreciation, although the author assumes full responsibility for any errors of commission or omission: Kenneth E. Corrigan, Ph.D.; Gerald E. Swindell, M.S.; Jack S. Krohmer, M.A.; and Lawrence Brown, Ph.D. Several commercial organizations have been most cooperative in furnishing data on various types of equipment and devices: Picker X-ray Corporation; High Voltage Engineering Corporation; General Electric X-ray Corporation; Tracerlab, Inc.; Victoreen Instrument Company; Nuclear-Chicago Corporation; Machlett Laboratories, Inc.; Gilbert X-ray Company of Texas; and North American Philips Company, Inc. Thanks are also due those authors and publishers who so generously permitted the use of their published data, as well as those whose original ideas and works bear the mark of anonymity.

Special recognition must be given the artist, Howard Marlin, for his admirable execution of the illustrations from the sketches provided by the author. The author's secretary, Mrs. Charlene Lane, should also be mentioned with gratitude for her diligence in typing the major part of the manuscript, including the tables.

Finally, the interest and encouragement of Charles C Thomas, Publisher, and their most competent staff are greatly appreciated, as have been their invaluable suggestions during the preparation of the manuscript.

JOSEPH SELMAN, M.D.

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CHAPTER 1

MATHEMATICAL BASIS OF RADIOTHERAPY

From its earliest days physics has evolved hand-in-hand with mathematics to reach its present advanced position. Moreover, mathematics continues to serve the physicist in a number of ways. Not only does it facilitate the comprehension of physical principles, but it also aids in the correlation of experimental and practical data. In some instances, it may even entail the development of new concepts.

For the student of radiologic physics, mathematics is essential both as an aid to learning and as a means of handling the data pertinent to radiation therapy. Since an insight into the physics of radiation therapy may be gained without resorting to higher mathematics, only those mathematical processes that are applicable to this field will be presented here.

PROPORTION

One of the more fundamental mathematical concepts is ***proportion,*** which simply expresses the equality of two ***ratios*** or ***fractions.*** Three main types of proportion are used in radiologic physics: (1) simple direct proportion, (2) simple inverse proportion, and (3) inverse square proportion.

Direct Proportion. One may represent simple ***direct proportion*** in three ways: ***algebraic*** or ***arithmetic, geometric,*** and ***graphic.***

1. ***Algebraic or Arithmetic Method.*** At a half price sale the ratio ½ indicates the fraction by which the list price would be reduced on any given article. Thus, if an item were marked $2.00, its sale price would be $1.00. To represent such a simple situation in algebraic terms immediately establishes the basic concept of proportion. In a half-price sale, if the list price of a given item is $6.00, its sale price x can be found according to the proportion:

$$\frac{x}{6} = \frac{1}{2}$$

Solving this equation by cross-multiplication,

$$2x = 6$$

$$x = 3 \text{ dollars, } \textit{the sale price}$$

Direct proportion can be stated ***algebraically*** as follows:

$$\frac{y}{x} = \frac{b}{a} \qquad (1)$$

This means that y is as many times greater than x, as b is greater than a. The ratio y/x equals the ratio b/a. If any three of these factors are known, the fourth can easily be determined by equation (1).

Note that in any given proportion, the ratio is constant. Thus, in equation (1), b/a is a constant. Substituting the constant k for b/a in equation (1),

$$\frac{y}{x} = k$$

$$y = kx \qquad (2)$$

k is called the ***constant of proportionality.*** Whenever a variable such as y (known as the *dependent variable*) is proportional to another variable such as x (known as the *independent variable*), it equals a constant times the variable, as noted in equation (2). y is said to be a function of x, often expressed as $y = f(x)$. Only if you know the constant of proportionality, can you find the dependent variable for a given independent variable.

2. ***Geometric Method.*** When two triangles have the same shape, but differ in size, they are said to be ***similar triangles.*** The corresponding sides (ie, the sides opposite the equal angles) are proportional. Figure 1.01 shows the proportionality of the corresponding sides in the similar triangles abc and ABC:

$$AB/ab = AC/ac$$

$$AB/ab = BC/bc$$

$$BC/bc = AC/ac$$

In other words, the ratio of any two corresponding sides is the same as that of any other two corresponding sides.

Since the corresponding sides of similar triangles are also proportional to their heights, one can apply this principle to the relationship

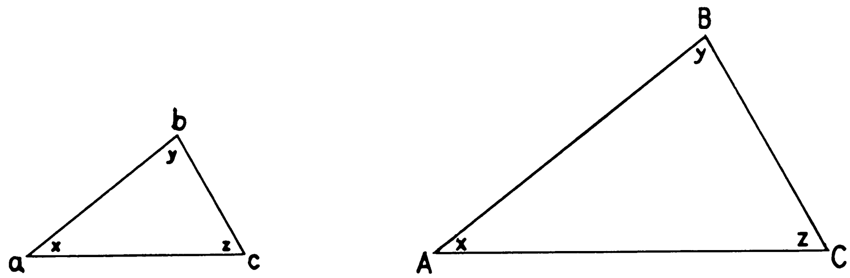

FIGURE 1.01. Similar triangles *abc* and *ABC*. $AB/ab = BC/bc = CD/cd$ because the corresponding sides are directly proportional when the corresponding angles are equal.

between the width of an x-ray beam and the distance from the source. Figure 1.02 shows a smaller triangle *ABC* superimposed on the larger triangle *ADE;* the sides *AC* and AE represent the edges of a beam. Triangle *ABC* is similar to triangle *ADE.* Therefore the widths of the beam such as *BC* and *DE* are proportional to their respective heights d_1 and d_2. Thus,

$$BC/DE = d_1/d_2$$

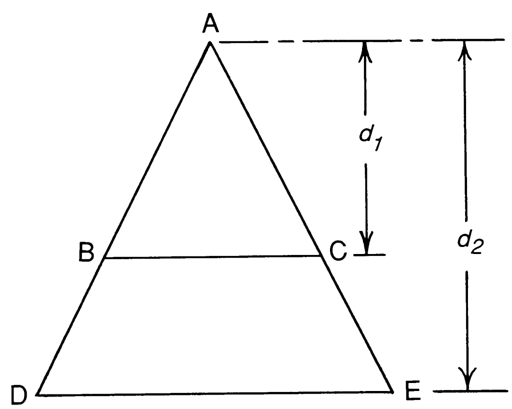

FIGURE 1.02. The corresponding sides of similar triangles are proportional to their heights. This principle can be applied to the relation between the width of an x-ray beam and its distance from the source. The smaller triangle *ABC* is superimposed on the larger triangle *ADE,* and the sides of the triangles represent the edges of the diverging beam. Since triangle *ABC* is similar to triangle *ADE,* the widths of the beam such as *BC* and *DE* are proportional to their respective distances (heights d_1 and d_2), so $BC/DE = d_1/d_2$, when the beam originates at a point source.

when the beam originates from a point source.

3. ***Graphic Method.*** A simple direct proportion may be expressed as a graph. For example, the width of an x-ray beam is directly proportional to the source-skin distance. If a series of measurements of beam width as a function of source-skin distance is arranged as in Table 1.01, you can see that the ratio of any beam width to its corresponding distance, such as 8/10, is the same as that of any other, such as 24/30. In both cases, the ratio reduces to 4/5.

TABLE 1.01
DATA ILLUSTRATING SIMPLE DIRECT PROPORTION: THE RELATIONSHIP OF BEAM WIDTH TO DISTANCE FROM SOURCE

Source-Skin Distance	*Beam Width*	*Ratio of Beam Width to Distance*
cm	*cm*	
10	8	8/10 = 4/5
20	16	16/20 = 4/5
30	24	24/30 = 4/5
40	32	32/40 = 4/5
50	40	40/50 = 4/5

This information, plotted as a ***graph*** in Figure 1.03, generates a curve—a straight line with its origin at 0. The ***slope*** of the curve is the ratio of the vertical distance of any given point to its ***horizontal distance*** from the origin (ie, the ratio of the y to the x coordinate). For example, the vertical dotted line intersects the curve at twenty-four units above the origin, and also intersects the horizontal line at thirty units from the origin. The ***slope*** is therefore 24/30 = 4/5. Stated algebraically, if y is the field width and x is the source-skin distance,

$$y = \frac{4}{5} x$$

Note that the constant of proportionality and the slope of the curve are exactly the same, in this case 4/5. Thus, for any distance x, the field width y can readily be determined either from the graph or from its algebraic counterpart.

Simple direct proportion has wide application in radiology. For example, all other factors being equal, radiation dose D is proportional to the exposure time t. Therefore, the equation for dose as a function of time is