

THE BASIC PHYSICS
of
RADIATION THERAPY
Third Edition

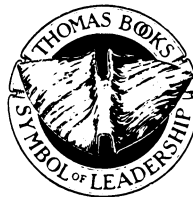
THE BASIC PHYSICS of RADIATION THERAPY

Third Edition

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 radia-

tion 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.

CONTENTS

	<i>Page</i>
<i>Preface to the Third Edition</i>	v
<i>Preface to the Second Edition</i>	ix
<i>Preface to the First Edition</i>	xi
<i>Chapter</i>	
1. MATHEMATICAL BASIS OF RADIOTHERAPY	3
Proportion	3
Direct proportion	3
Inverse proportion	7
Inverse square proportion	10
Mathematical law of decay	14
Significant figures	17
Decimal system and scientific notation	19
Units of measurement	22
Standard units	22
Fundamental units	23
Derived units—general	24
Derived units for electric currents	26
Units in Radiologic Physics	27
Temperature	28
Naming and use of units	29
Prefixes applied to defined units	29
International system of units (SI)	30
2. MATTER AND ENERGY	32
Historical background	32
Dalton's theory	32
Avogadro's law	33
Prout's hypothesis	33
Mendeléev's law	33
Arrhenius' theory	35

Avogadro's number	35
States of matter	36
Atomic and molecular size	37
Structure of the atom	38
Present concept of atomic structure	39
Nucleus	39
Orbital electrons	41
Atomic number	46
Mass number	47
Equivalence of mass and energy	48
3. THE NATURE OF RADIATION	53
Types of radiation	53
Electromagnetic radiation	54
Dual nature	56
Particulate radiation	57
Detection of particulate radiation	57
Wilson cloud chamber	57
Glaser bubble chamber	58
Alpha particles	59
Beta ⁻ particles	62
Beta ⁺ particles	66
Neutrons	67
Orbital electrons	69
Cosmic rays	70
Summary	70
4. KILOVOLTAGE X-RAY PRODUCTION, PROPERTIES, AND EQUIPMENT	72
Historical introduction	72
Evolution of the x-ray tube	74
Conditions required for the production of x rays	75
Essential features of kilovoltage x-ray tubes (100–300 kVp)	77
Glass envelope	77
Cathode assembly	77
Anode (target)	77
Large potential difference	79
Small tube current	80

Electron interactions with target atoms	81
Bremsstrahlung	81
Characteristic radiation	82
Efficiency of x-ray production	84
Properties of x rays	85
Generation and regulation of kilovoltage	86
High-voltage transformer	86
Voltage-control devices	87
Autotransformer	87
Rheostat	88
Regulation of tube current	89
Rectification	89
Cables	92
Orthovoltage x-ray beams in radiotherapy	93
Cones	93
Lead aperture shields	94
5. HIGH-ENERGY THERAPY UNITS:	
PARTICLE ACCELERATORS	96
Telecurie therapy	97
Cobalt-60 therapy equipment	97
Source	98
Housing	100
Beam limitation (collimation)	101
Cesium-137 teletherapy equipment	103
Megavoltage x-ray generators	104
Van de Graaff x-ray generator	104
Linear accelerator	106
Principle	106
Internal components and operation	106
External components	110
X-ray target	111
Beam-flattening filter	111
Scattering foil or Scanning magnet	112
Monitor ionization chambers	112
Beam limitation (collimation)	113
Field illuminator and rangefinder	113

Shadow tray	114
Betatron	114
Microtron	116
Heavy charged-particle accelerators	117
Cyclotron	118
Synchrocyclotron	122
Synchrotron	122
Electron synchrotron	123
Proton synchrotron	123
6. INTERACTIONS BETWEEN IONIZING RADIATION AND MATTER	125
Photon interactions with matter	125
Photon-beam attenuation in matter	126
Half-value layer	130
Monoenergetic radiation	130
Polyenergetic radiation	132
Derived attenuation coefficients	136
Energy-transfer and absorption coefficients	137
Interactions between photons and atoms	138
Coherent scattering	138
Photoelectric interaction	139
Compton interaction with modified scattering (photons)	142
Compton mass-attenuation coefficient	146
Compton energy-transfer and absorption	146
Pair and triplet production	147
Pair energy-transfer and absorption	148
Bremstrahlung in the Compton and pair processes	149
Relative importance of various photon interactions	149
Interactions of charged particles with matter	151
Alpha particles	152
Beta ⁻ particles	152
Elastic interactions	152
Inelastic interactions	153
Beta ⁺ particles	154
Characteristic or fluorescent radiation	154

7. EXPOSURE AND EXPOSURE RATE OF PHOTON BEAMS	158
Introduction	158
Beam terminology	158
Photon fluence	158
Energy fluence	159
Energy fluence rate (intensity; flux density)	159
Definition of the roentgen	160
Measurement of the roentgen	162
Capacitor ion chambers	166
Thimble and capacitor	167
Electrometer	170
Units of radiation exposure and absorbed dose	172
Roentgen (R)	172
Centigray (rad)	173
Factors affecting kilovoltage x-ray output	173
Tube potential	173
Tube current	174
Distance	174
Filtration	176
Energy transfer	176
Photon scatter	176
Factors affecting gamma-ray exposure	177
8. X-RAY QUALITY	178
Analysis of x-ray beams	178
Modification of kilovoltage beams by filters	183
Specification of x-ray quality in radiotherapy	187
Half-value layer	188
Tube potential	192
Other methods of specifying x-ray quality	192
Equivalent constant potential	193
Equivalent photon energy	193
9. ABSORBED DOSE IN TELETHERAPY WITH PHOTONS	195
Introduction	195
Absorbed dose	195

Transfer of photon energy to orbital electrons (kerma) . . .	195
Absorption of electron energy by medium (absorbed dose) .	195
Relation of absorbed dose to exposure	197
Absorbed dose in “free space”	199
Absorbed dose in any medium	201
Bragg-Gray cavity theory	201
Calibration of megavoltage photon beams	203
Modification of Bragg-Gray theory (Spencer-Attix)	205
Conditions needed to implement AAPM	
calibration protocol of 1983	206
Dose-to-plastic to dose-to-water correction	207
Beam quality (nominal accelerating potential)	208
Dosimeters	209
Buildup caps	211
The cavity-gas calibration factor N_{gas}	212
Explanation of the basic equation in the AAPM protocol	213
Steps in calibrating a megavoltage x-ray beam	219
Calibration of a cobalt beam	221
Calibration of kilovoltage x-ray beam (100–300 kVp)	224
Calibration of very low-kilovoltage x-ray beams	227
Postscript to AAPM protocol	228
Other methods of measuring absorbed dose	229
10. CENTRAL-AXIS DOSE DISTRIBUTION	
WITH PHOTON BEAMS	232
Introduction	232
Electron buildup	232
Backscatter and peak scatter factor	235
Quality of radiation	238
Size of treatment field	238
Field shape	241
Peak scatter factor	241
Percentage depth dose (PDD)	242
Factors in PDD	244
Beam quality	244
Depth of lesion	246
Size of treatment field	246
Source-surface distance (SSD)	251

Tissue-air ratio (TAR)	255
Factors in TAR	257
Beam energy	257
Depth in medium	258
Field area	258
Relationship between TAR and PDD	259
Tissue-phantom ratio (TPR) and tissue-maximum ratio (TMR) .	261
Corrections for tissue inhomogeneities	264
Correction for lung transmission	264
Correction for bone “shadowing”	266
Effect of air cavity on dose buildup	267
Exit dose	268
11. DOSE DISTRIBUTION WITH PHOTON BEAMS	271
Single beams	271
Factors affecting isodose distributions	274
Beam quality	274
percentage depth dose	274
depth of isodose curves	274
sharpness of beam margins	274
Penumbra	275
Beam-flattening filter	275
Field size	276
Multiple beams	276
Parallel opposed fields	277
Source-surface distance (SSD)	277
Source-axis distance (SAD)	278
Central axis doses	279
Composite isodose charts for several fields	280
Absorbed dose distributions at critical points only	284
Arrangement of multiple fields	286
Methods of beam modification	288
Wedge filters	289
Treatment distance with wedged fields	294
Types of wedges	295
Construction of wedges	296
Precautions in the use of wedges	298

Correction for sloping skin surfaces	299
Bolus	299
Tissue-compensating filters	300
Isodose-shift method	301
Rotation therapy	302
Principles	302
Practical aspects	305
Size of field	305
Size of penumbra	305
Energy of radiation	305
Source-axis distance	305
Shape of patient	305
Partial (arc) rotation	306
Modification by wedge	306
Scatter analysis	307
Principles	307
Average TMR for irregular fields	309
Calculation of dose under a block	313
12. THERAPY PLANNING WITH PHOTON BEAMS	315
Introduction	315
Tolerance doses	315
Megavoltage-beam parameters	317
Beam energy	317
Treatment distance	319
Field flatness and symmetry	320
Field flatness	320
Field symmetry	320
Beam delimitation (collimation)	321
Beam	321
Beam axis	321
Mechanical	321
Geometric	322
Dosimetric	322
Field size	322
Geometric	322
Physical	322

Penumbra	322
Geometric.....	322
Physical	325
Field matching	327
Contamination of photon beams by electrons and neutrons...	330
Electron contamination of photon beams.....	331
Neutron contamination of photon beams.....	331
Control of dose delivery	332
The therapy planning process	333
Outline of steps in therapy planning	333
Photography of patients	333
Localization of target volume	334
Simulation	334
Planning of dose distribution	334
Verification	334
Dosimetry.....	334
Localization of target volume	334
Simulation	335
Simulator features	335
Simulator use	336
Field shaping with custom blocks	337
Custom block-cutter	337
Fabrication of custom blocks	337
Execution of treatment plan	340
Selection of therapy beam.....	340
Electron beam	341
Photon beam	341
Beam modification	341
Wedges	341
Tissue compensators	341
Bolus.....	342
Selection of fields	342
Photography of fields	342
Dosimetry in fixed-beam therapy	343
Orthovoltage x-ray beam.....	344
Single fixed megavoltage-photon beam, SSD.....	345

Single fixed megavoltage-photon beam, SAD	345
Parallel opposed beams, SSD	346
Parallel opposed beams, SAD	346
Three-field megavoltage-photon beams, SAD	346
Dosimetry in moving-beam photon therapy	348
Body contour	349
Target volume	349
Moving-beam positions	349
Selection of critical dose points	349
Average TMR at isocenter	350
Isodoses and TMRS at critical points	350
Moving-beam therapy, full 360° rotation	352
Moving-beam arc therapy, 270° rotation	353
Moving-beam therapy with cobalt 60	353
Recommended normalization of isodose curves	354
Examples of computer-generated isodose charts	355
13. ELECTRON-BEAM THERAPY	362
Introduction	362
Electron-beam energy	363
Electron ranges	364
Percentage depth doses	366
Electron-beam isodose curves	368
Penumbra	372
Modification of isodose curves	373
Sloping surfaces	373
Convex surfaces	373
Corrections for tissue inhomogeneities	376
Bone	377
Air cavity	377
Position of virtual source	377
Field-size dependence	379
Output	379
Percentage depth dose	379
Equivalent squares	382
Field shaping	382
Adjoining-field therapy	384

X-ray contamination of electron beams	384
Application of electron-beam physics in radiotherapy	386
Selection of beam energy	387
Selection of field size	387
Surface dose	388
Combined electron and photon radiotherapy	388
Boost therapy with electrons	388
Concurrent therapy with electrons and photons	389
Rotation therapy with electrons	389
Calibration of electron beams	390
AAPM Protocol TG-21 – (1983)	390
Electron-beam energy	391
Ion chambers	391
Cylindrical chamber	392
Plane-parallel chamber	392
Dosimetry phantoms	392
Equation for dose-to-medium	393
Application of AAPM Protocol to electron beams: summary	394
Energy range of electrons	395
Primary dosimeter	395
Phantom material	395
Depth of calibration	395
Steps in calibration	395
Dose-to-gas	395
Dose-to-medium	395
14. RADIOACTIVITY AND NUCLEAR PHYSICS	396
Definition	396
Historical background	396
Factors in nuclear stability	398
Neutron-proton ratio	398
Nuclear binding-energy	398
Nuclear short-range forces	398
Exchange forces	399
Odd-even rules	399
Types of nuclear decay	399

Alpha emission	399
Beta emission	400
Gamma emission	401
Gamma rays	402
Sources of gamma rays	403
Nuclear decay	403
Nuclear excitation	403
Energy of gamma rays (methods of determination)	404
Crystal diffraction	404
Photoelectric interaction	404
Internal conversion	405
Pair spectrometry	405
Scintillation spectrometry	405
Induction of artificial radioactivity	405
Activation of atoms—nuclear reactions	408
Neutron reactions	408
Slow-neutron reactions	408
Fast-neutron reactions	409
Proton reactions	410
The radioactive decay process	412
Displacement law	414
Radioactive decay schemes	414
Units of activity	415
Mathematical law of decay—decay constant	416
Half-life	418
Average life	421
Specific activity	422
Exposure-rate constant	423
Radioactive equilibrium	425
Secular	425
Transient	427
Nuclear reactor	428
The fission process	428
Nuclear reactor operation	432
Nuclear fusion	436
Practical applications of nuclear reactor	437

15. BRACHYTHERAPY WITH RADIUM AND ARTIFICIAL RADIONUCLIDES	440
Historical survey	440
Radium	441
Types of radium applicators	443
Needles	443
Tubes	444
Dosimetry in brachytherapy	445
Introduction	445
Distribution systems in brachytherapy	445
Derivation of distribution systems	445
Exposure-rate constant	445
Exposure rates near linear sources	450
Basic interval method	450
Modified interval method	452
Conversion of exposure to absorbed dose	453
The time-intensity factor	459
Intracavitary therapy with linear sources	460
Simple linear arrangement	461
Complex array of sources	462
Interstitial brachytherapy	466
Paterson-Parker (Manchester system)	468
Correction factors	469
Planar implant	469
Volume implant	474
Quimby system	479
Planar implant	480
Volume implant	481
Artificial radionuclides in interstitial therapy	482
Surface brachytherapy with gamma rays	484
Methods of verifying implants	487
Manual	487
Computer-generated	490
Dose specification for radium substitutes	491
Summary of radionuclides available for brachytherapy	494
Surface therapy with beta particles	498

	⁹⁰ Strontium- ⁹⁰ Yttrium ophthalmic applicator	499
	Personnel protection	502
16.	CANCER THERAPY WITH RADIOPHARMACEUTICALS	503
	Introduction	503
	Radionuclide instrumentation	505
	Radiation detectors	505
	G-M counter	505
	Scintillation counter	507
	Well counter	508
	Sources of error in counting	510
	Efficiency and sensitivity of counters	510
	Practical aspects of counting	511
	Geometric factors	511
	Methods of counting	511
	Absolute counting	512
	Comparative counting	512
	Whole-organ counting	512
	Decay constants and half-lives	513
	Systemic therapy with radionuclides	515
	Dosage	515
	Absorbed dose from beta emitters	516
	Absorbed dose from gamma emitters	518
	Examples of systemic therapy with radionuclides	519
	Radioactive iodine (¹³¹ I)	519
	hyperthyroidism	519
	thyroid cancer	519
	Radioactive phosphorus (³² P)	521
	polycythemia vera	521
	essential thrombocythemia	522
	metastatic carcinoma in bone	522
	Radiocolloid ³² P therapy of malignant effusions	523
17.	RADIOBIOLOGY	525
	Physical basis of radiobiology	525
	Introduction	525
	Absorbed dose	525

Linear energy transfer (LET)	528
Relative biologic effectiveness (RBE)	529
The Cell	530
Normal anatomy of the cell	531
Nucleus	531
Cytoplasm	532
Cellular renewal	533
Elementary genetics	533
Cell reproduction—mitosis	535
The “resting” or interphase period	536
Meiosis	537
Malignant cells	539
Modes of action of ionizing radiation on cells	540
Direct action	541
Indirect action	541
Formation of free radicals and aqueous electrons	541
Fate of free radicals and aqueous electrons	543
Fluid-flow theory	544
Radiation-induced injuries at the cellular level	544
Cell death	544
Reproductive death	544
Genetic death	544
Lytic death	545
Gene mutations and chromosome aberrations	545
Mutations	545
Aberrations	545
Mitotic inhibition	546
Assessment of cellular radiosensitivity: cell survival curves	547
Shoulder portion	549
Terminal exponential portion	548
Effect of high-LET radiation	550
Implications of exponential response	551
Mean lethal dose (D_o)	553
Quasi-threshold dose	554
Survival of irradiated cells	556
Modification of cellular response to irradiation	557

Fractionation and repair	558
Position of cell in reproductive cycle	559
Oxygenation	560
Ploidy	561
Radiation effects on cytoplasm	562
Growth of tumors	562
Doubling time	563
Potential doubling time	565
Response of neoplasms to irradiation	565
Radiosensitivity	565
Oxygen effect	567
Dose fractionation	570
Fractionation schedule in radiotherapy	571
Time-dose regression curves	572
The four Rs	574
Repair of sublethal injury	574
Reoxygenation	575
Repopulation	576
Redistribution	576
Volume effect	577
Radiation quality (low- and high-LET)	578
Dose-rate effect	579
Abscopal effect	580
Therapeutic ratio	581
Normal-tissue tolerance dose	581
Tumor-lethal dose	581
Hyperfractionation	582
Nominal standard dose (NSD)	584
Full tolerance	584
Partial tolerance	585
Acute whole-body radiation syndromes	592
Median lethal dose (LD ₅₀)	592
Description of acute radiation syndromes (ARS)	594
Subclinical syndrome	595
Hematopoietic syndrome	596
Gastrointestinal syndrome	596

Neurovascular syndrome	597
Cell population kinetics as the basis for ARS	597
Modification of cellular injury	601
Physical modifiers	602
Chemical modifiers	602
Radiation sensitizers	602
Radiation protectors	603
Physiologic modifiers	604
18. RADIOTHERAPY WITH HEAVY-PARTICLE BEAMS	606
Introduction	606
Neutron-beam therapy	606
Sources of neutrons	606
Deuterium-tritium generator	607
Cyclotron generator	607
Physical properties of neutrons	607
Depth-dose characteristics of neutron beams	608
Isodose distributions	608
Penumbra	608
Tissue inhomogeneities	609
Radiobiology of neutrons	609
Oxygen effect	609
Relative biologic effectiveness (RBE)	610
Oxygen enhancement ratio (OER)	610
Cell cycle	611
Cell survival curves	611
Neutron brachytherapy (californium 252)	613
Negative pi meson (pion) therapy	615
Proton-beam therapy	618
Helium-ion beam therapy	619
19. QUALITY ASSURANCE	623
Physical factors	623
Dose-rate stability	623
Timer and monitor ionization chamber	624
Treatment distance	624
Field size	624
Beam alignment	624

Beam quality	625
Field flatness and symmetry	625
Collimator-rotation readout	626
Gantry rotation readout	626
Stability of isocenter	626
Mechanical and electrical safety	627
Area monitoring	627
Control-panel meters	628
Labeling of auxiliary devices	628
Patient communication	628
Personnel factors	628
Assessment and localization	628
Dosimetry	628
Errors in patient setup	629
20. PROTECTION IN RADIOTHERAPY:	
HEALTH PHYSICS	632
Dose equivalent	632
Background radiation	634
External sources	634
Cosmic rays	634
Terrestrial radiation	634
Atmospheric radiation	635
Internal sources	635
Maximum permissible dose-equivalent (MPD)	637
Accumulated dose (occupational)	637
Emergency exposure (occupational)	638
Medical exposure (radiation workers)	638
Exposure of persons outside controlled areas	638
Summary of NCRP recommendations	639
Measurement of ambient radiation exposure	640
Personnel monitoring	640
Film badge	640
Self-reading pocket dosimeter	641
Pocket chamber	642
Thermoluminescent dosimeter (TLD)	642
Area radiation monitors	642

Protection surveys	643
Warning signs	645
Protective measures in photon-beam therapy	645
Beam components	645
Useful beam	645
Leakage radiation	645
Scattered radiation	645
Stray radiation	646
Radiation sources	646
Orthovoltage x-ray tubes	646
Linear accelerator housing	646
Telecobalt and telecesium sources	646
Protective wall barriers	646
Primary	646
Secondary	647
Location and specification of wall barriers	647
Application of inverse square law	647
Restriction in direction of useful beam	648
Attenuation of radiation by scattering	649
Computation of wall barrier for 8-hour day	649
Work load (W)	649
Use factor (U)	649
Occupancy factor (T)	649
Use of most efficient material	650
Allowance of safety factor	651
Example of computation for a teletherapy room	651
Primary protective barrier	653
Secondary protective barrier	655
barrier thickness for scattered radiation	655
barrier thickness for leakage radiation	657
Protective measures in brachytherapy	658
Protection against whole-body radiation	658
Storage of brachytherapy sources	658
Manipulation of brachytherapy sources	665
Transportation of brachytherapy sources	665
Hazards to nursing personnel in brachytherapy	665

Protection against local exposure	666
Hazards from radionuclides in teletherapy	667
Personnel hazards in nuclear medicine	669
External hazards (whole body)	670
Gamma radiation	670
Beta radiation	672
External hazards (local)	672
Internal hazards	673
Inhalation	673
Ingestion	673
Absorption through skin	674
Laboratory design and facilities	676
Shielding of stored radionuclides	676
Decay chamber	677
Area radiation monitoring	677
Disposal of radioactive wastes	678
Sewage disposal	678
Incineration	678
Decontamination	679
Recommendations for nursing procedures	679
Special instructions with radiiodine 131 (^{131}I)	680
Special instructions with radiophosphorus 32 (^{32}P)	682
Special instructions with radium substitutes	683
Unsafe procedures in handling unsealed radionuclides	683
Inadequate planning of procedures	683
Improper monitoring	683
Inadequate shielding	683
Inadequate use of trays and paper covering	684
Pipetting of solutions by mouth	684
Poor work habits	684
Inadequate use of protective clothing	684
Improper disposal	684
Inadequate fume hoods	684
Changing types or levels of activity and procedures	684
Failure to maintain detailed radiation safety records	684
Failure to post signs	684

<i>Appendix</i>	685
Central axis dose distributions (Tables 1–14)	686
Useful physical data (Table 15)	708
Useful equations (Table 16)	709
The Greek alphabet (Table 17)	713
<i>References</i>	715
<i>Index</i>	723

THE BASIC PHYSICS
of
RADIATION THERAPY
Third Edition

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 $\frac{1}{2}$ 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,

$$2x = 6$$

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

Direct proportion can be stated *algebraically* as follows:

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

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),

$$\begin{aligned} \frac{y}{x} &= k \\ y &= kx \end{aligned} \quad (2)$$

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

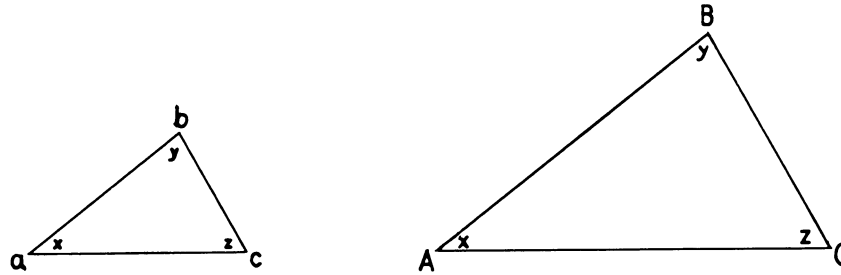


FIGURE 1.01. Similar triangles abc and ABC . $AB/ab = BC/bc = CD/cd$ because the corresponding sides are directly proportional when the corresponding angles are equal.

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,

$$BC/DE = d_1/d_2$$

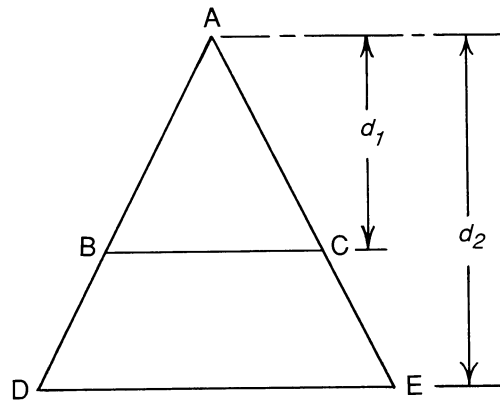


FIGURE 1.02. The corresponding sides of similar triangles are proportional to their heights. This principle can be applied to the relation between the width of an x-ray beam and its distance from the source. The smaller triangle ABC is superimposed on the larger triangle ADE , and the sides of the triangles 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

<i>Source-Skin Distance</i>	<i>Beam Width</i>	<i>Ratio of Beam Width to Distance</i>
<i>cm</i>	<i>cm</i>	
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