

THE PHYSICS OF RADIOLOGY

FOURTH EDITION

HAROLD ELFORD JOHNS

O.C., Ph.D., F.R.S.C., LL.D., D.Sc.

*University Professor Emeritus, University of Toronto
Professor Emeritus, Department of Medical Biophysics and
Department of Radiology, University of Toronto
Former Head of, and now consultant to, the Physics Division,
Ontario Cancer Institute and the Radiological Research Laboratories,
University of Toronto*

JOHN ROBERT CUNNINGHAM

B.Eng., M.Sc., Ph.D.

*Senior Clinical Physicist, Ontario Cancer Institute
Professor, Department of Medical Biophysics
University of Toronto*

Authority, comprehensivity and a consummate manner of presentation have been hallmarks of *The Physics of Radiology* since it first saw publication some three decades past. This Fourth Edition adheres to that tradition but again updates the context. It thoroughly integrates ideas recently advanced and practices lately effected. Students and professionals alike will continue to view it, in essence, as the bible of radiological physics.

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THE PHYSICS OF RADIOLOGY

Although it follows the topical outline that proved so successful in its earlier editions, the Fourth Edition of this respected book encompasses all of the advances and changes that have been made since last it was revised. It not only presents new ideas and information, it shifts its emphases to accurately reflect the inevitably changing perspectives in the field engendered by progress in the understanding of radiological physics.

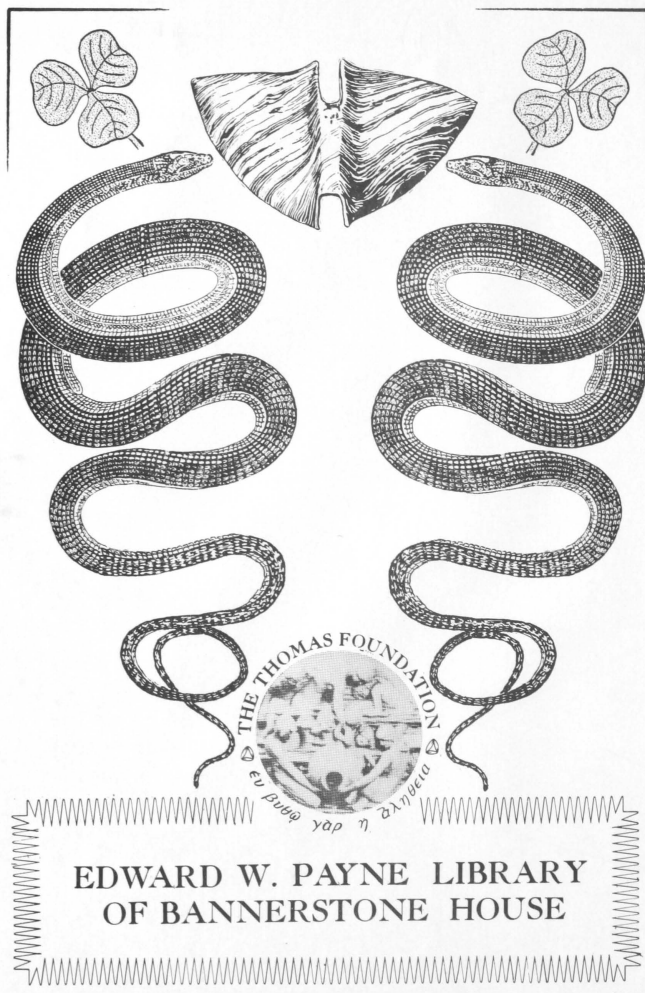
A chapter on basic concepts lays the foundation for subsequent discussions of x-ray properties and production, nuclear physics, and high energy machines. Examinations of the interaction of radiation with matter, radiation dosimetry, the quality of x rays, instruments and techniques for radiation measurement, and the interaction of beams with a scattering medium follow. Later chapters in the text move toward clinical topics with coverage of treatment planning, brachytherapy, nuclear medicine, radiation protection, diagnostic radiology and radiobiology.

Among the newer trends, techniques and concepts covered are the continuing shift to high energy photon use in radiotherapy, the refinement of radiation dosimetry theory and practices, and the prodigious advances in imaging and diagnosis afforded by such advances as computerized tomography. Similarly, the authors have integrated the concept of relative risk in radiation protection and the increasingly greater stress in radiobiology on humans rather than animals or cells.

The effectiveness of the book as both text and reference has been maintained through ongoing scrutiny of ways in which to match it to progress made in the field. Thus, the advent and widespread availability of small calculators and refined computers are reflected in the way calculations and problems are presented. And the broad dissemination of sources of radiological data has brought about a shift in the focus of information given in the appendices: these now contain more basic radiological material, but are more specifically correlated with the textual content than before.

(continued on back flap)

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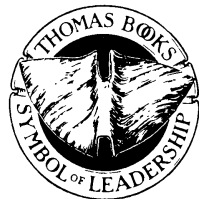
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and

JOHN ROBERT CUNNINGHAM, B.Eng., M.Sc., Ph.D.

Senior Clinical Physicist, Ontario Cancer Institute

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PREFACE

Since the publication of the Third Edition of *The Physics of Radiology*, various international organizations have attempted to introduce SI (système international) units into their fields. Of particular interest to us are the new terms that have been defined for the radiological sciences: the *gray* has replaced the rad as the unit of absorbed dose, and the *becquerel* has replaced the curie as the unit of activity.

We are convinced of the advantages of SI and the new units are used throughout the book. We realize, however, that it will take some time before workers in the field are at ease with them and for this reason the older units are often used in parallel with the new ones.

Committees of the I.C.R.U. are attempting to deemphasize the use of the roentgen as a unit of exposure. In spite of this we have continued to use it, especially in diagnostic radiology. When patients are exposed to soft x rays, as they are in diagnostic radiology, there is no single factor which allows one to go from exposure to dose. The authors feel that the I.C.R.U. has not adequately assessed the impact of their decision on this subject. Because the roentgen remains a practical unit, the chapter on diagnostic radiology still makes extensive use of it.

The use of small electronic calculators has relieved the scientist of many of the boring arithmetical tasks of the past. We believe that all scientists now use calculators, and we have felt at greater liberty to do calculations that involve logarithms or exponentials, a procedure which was previously more difficult. In addition, we have introduced, in the first chapter, exponential growth and decay, since it is common to all aspects of radiation and since, for example, we believe the doubling time for the growth of cells is no more complicated a concept than the determination of the doubling time of invested money, a topic which everyone understands.

The emphasis in radiation therapy has shifted further towards the use of high energy beams. We therefore give less attention to cobalt 60 and more to the higher energy radiation produced by linear accelerators in the 10 to 25 MeV range.

There have been explosive developments in diagnostic radiology with the invention and exploitation of the CT scanner. In addition, other methods of imaging are rapidly becoming available. We have, therefore, more than doubled the size of the chapter on this subject. In addition,

because of the general fear of radiation, we have emphasized the idea that for every risk there should be a benefit and have discussed ways of reducing this risk without loss of diagnostic information.

In the chapter on radiobiology we have removed some basic radiation chemistry and replaced it with discussions on survival curves of patients so that the reader will have ways of comparing the results of different modes of treatment.

We are especially indebted to R.J. Howerton of Lawrence Livermore Laboratory for supplying us with a library of photon interaction coefficients on magnetic tape and to Dr. M.J. Berger of the National Bureau of Standards for supplying us with his latest calculations of electron stopping powers. The helpful discussions we have had with Mr. J.H. Hubbell, Dr. R. Loevinger, and Dr. S. Domen, all of the U.S. National Bureau of Standards, on topics of radiation dosimetry are much appreciated. Similarly, helpful correspondence and discussions on stopping powers with M. Pages of Centre d'Études Nucléaires de Saclay, France, are acknowledged. In addition, our association with members of AAPM Task Group 21 on High Energy Dose Calibrations has helped to clarify many concepts dealt with in this book.

We thank Dr. P. Leung, Mr. A. Rawlinson, Mr. J. Van Dyk, and Dr. P. Shragge for many discussions on clinical radiation physics and Dr. G. Ege and Dr. M. Bronskill for their help with the chapter on Nuclear Medicine.

In preparing Chapter 15 on radiation protection we were helped by Dr. H.O. Wyckoff of the ICRU, Washington; Dr. H. Johnston and Dr. C.L. Greenstock of Atomic Energy of Canada, Whiteshell, Manitoba; Dr. G. Cowper and Dr. A.M. Marko of the Chalk River Laboratories of Atomic Energy of Canada; Dr. M. James of the Atomic Energy Control Board, Ottawa; and Dr. D. Grogan of the Health Protection Bureau, Ottawa.

We are greatly indebted to Dr. K.W. Taylor, of the Radiological Research Laboratory, University of Toronto, who worked with us over a period of three years to create the chapter on diagnostic radiology. Valuable assistance in this task was also provided by Dr. M. Yaffe, Dr. A. Fenster, and Dr. A. Holloway, all of whom are closely associated with us.

The chapter on radiobiology was created in collaboration with Dr. R.P. Hill and valuable discussions on this topic were held with Dr. G. DeBoer, Dr. R.S. Bush, Dr. G.F. Whitmore, Dr. J.W. Hunt, Dr. A.M. Rauth, and Dr. W.D. Rider of our Institute.

We thank Dr. R.S. Bush, Dr. W.D. Rider, and the late Dr. C.L. Ash for their efforts at keeping our writings relevant to clinical problems.

We also acknowledge the help of our radiation oncology residents and radiation physics students who provided criticism and worked many of

the problems. In particular we mention Luis Cabeza, David Hunter, Paul Johns, Gordon Maudsley, Henriette Von Harpe, and John Wong.

The Ontario Cancer Institute continues to be a research facility in which ideas are fully exchanged and discussed and this kind of environment is essential to produce a book of this complexity. We acknowledge the leadership of its director, Dr. R.S. Bush.

We thank Mr. D. McCourt of the Ontario Cancer Institute who drafted over 200 diagrams for the book and Mr. A. Connor and his staff of our photography department who prepared them for publication. We thank Miss C. Morrison, Librarian at OCI, and her staff for helping with the references. We are most deeply indebted to and do sincerely thank our personal secretaries, Mrs. Stellis Robinson and Miss Ann Lake, for all they have done in the preparation of this manuscript.

In the thirty years that Charles C Thomas, Publisher, has been our publisher we have always been able to count on its understanding and support.

The writing of a book of this complexity, spread as it was over the past five years, needed the continuous support and encouragement of our wives and families, and this is gratefully acknowledged.

Harold E. Johns
J.R. Cunningham

CONTENTS

	<i>Page</i>
<i>Chapter 1</i> BASIC CONCEPTS	3
1.01 Introduction	3
1.02 Quantities and Units	3
1.03 Atoms	12
1.04 The Nucleus	13
1.05 Elemental Particles	15
1.06 Extranuclear Structure	15
1.07 Atomic Energy Levels	18
1.08 Nuclear Energy Levels	19
1.09 Electromagnetic Radiation	20
1.10 Quantum Nature of Radiation	21
1.11 The Electromagnetic Spectrum	22
1.12 Radiation of Energy from an Atom	24
1.13 Mass and Energy	25
1.14 Mass and Velocity	26
1.15 Exponential Behavior	27
1.16 Exponential Decay of a Radioactive Isotope— Half-Life	28
1.17 Transformation Constant	30
1.18 Exponential Growth of Money	31
1.19 Exponential Growth of Cells	32
1.20 Exponential Killing of Cells	32
1.21 Exponential Attenuation	33
1.22 Summary of Exponential Behavior	33
 <i>Chapter 2</i> THE PRODUCTION AND PROPERTIES OF X RAYS	 37
2.01 The X Ray Tube and Simplified Circuit	37
2.02 Self-Rectified X Ray Circuit	39
2.03 Rectification	43

	<i>Page</i>
2.04 Three Phase Units	45
2.05 Anode and Cathode Structures	48
2.06 Ratings of Diagnostic Tubes	53
2.07 X Ray Spectra	59
2.08 Interactions of Electrons with the Target to Give X rays	60
2.09 Characteristic Radiation	62
2.10 White Radiation or Bremsstrahlung	64
2.11 The Angular Distribution of X Rays	66
 <i>Chapter 3</i> THE FUNDAMENTALS OF NUCLEAR PHYSICS ..	 71
3.01 Natural Radioactivity	71
3.02 Artificial Radioactivity	71
3.03 Activity	72
3.04 Emitted Radiation (Average or Mean Life)	74
3.05 Charts of Isotopes	76
3.06 Alpha Disintegration	77
3.07 Beta Disintegration	79
3.08 Beta Minus Decay	81
3.09 Beta Plus Decay	84
3.10 Electron Capture (EC)	85
3.11 Internal Conversion	86
3.12 Auger Electrons	88
3.13 Isomeric Transitions	89
3.14 Energy Absorption from Radioactive Isotopes	90
3.15 Decay Series	91
3.16 Growth of Radioactive Daughter	92
3.17 Nuclear Fission	94
3.18 Nuclear Fusion	95
3.19 Activation of Isotopes	96
3.20 Activity Produced by Neutron Irradiation	99
 <i>Chapter 4</i> HIGH ENERGY MACHINES	 102
4.01 Introduction	102
4.02 Considerations in the Design of High Energy Beams ..	103
4.03 Betatrons	106
4.04 The Linear Accelerator (LINAC)	108
4.05 Medical Linacs	111
4.06 Isotope Machines	118
4.07 Typical Cobalt 60 Units	120

Page

4.08	The Cyclotron	125
4.09	Particles for Radiotherapy	127
<i>Chapter 5</i>	THE INTERACTION OF IONIZING RADIATION WITH MATTER	133
5.01	Absorption of Energy	133
5.02	Linear Attenuation Coefficient and Exponential Attenuation	134
5.03	Half-Value Layer	137
5.04	Narrow and Broad Beams	139
5.05	Mass, Electronic, and Atomic Attenuation Coefficient	140
5.06	Energy Transfer and Energy Absorption	143
5.07	Photoelectric Absorption	146
5.08	Scattering—Coherent and Incoherent	149
5.09	Compton Cross Sections	151
5.10	Pair Production	155
5.11	Total Attenuation Coefficient	158
5.12	Total Transfer and Absorption Coefficients	161
5.13	The Relative Importance of Different Types of Interactions	161
<i>Chapter 6</i>	THE BASIC INTERACTIONS BETWEEN PHOTONS AND CHARGED PARTICLES WITH MATTER	167
6.01	Photoelectric Effect	167
6.02	Thomson Scattering (Classical Scattering)	168
6.03	Coherent Scattering (Rayleigh Scattering)	172
6.04	Energy-Angle Relations in a Compton Collision	173
6.05	Probability of Compton Collision (Klein-Nishina Coefficients)	176
6.06	Energy Distribution of Compton Electrons	179
6.07	Effect of Binding Energy on Compton (Incoherent) Scattering	181
6.08	Pair and Triplet Coefficients	184
6.09	Energy Distribution of Electrons and Positrons Produced in Pair Production	184
6.10	Multiple Processes, Monte Carlo Calculations, Case History	186
6.11	Interaction of Heavy Charged Particles with Matter ..	190

	<i>Page</i>
6.12 Interaction of Electrons with Matter	193
6.13 Range of Electrons and Bremsstrahlung Yield	197
6.14 Energy Distribution of Electrons Set in Motion in a Medium Exposed to Monoenergetic Photons	200
6.15 Energy Spectrum of Electrons “Seen” in the Medium ..	204
6.16 Mean Stopping Powers	208
6.17 Restricted Stopping Powers and Linear Energy Transfer (LET)	211
 <i>Chapter 7</i> MEASUREMENT OF RADIATION: DOSIMETRY	217
7.01 Quantities to Describe a Radiation Beam	217
7.02 Energy Transfer—A Two Stage Process—Kerma and Absorbed Dose	218
7.03 Electronic Equilibrium	220
7.04 The Bragg-Gray Cavity	224
7.05 Determination of Absorbed Dose Using an Absolute Ion Chamber	228
7.06 Effects of Temperature and Pressure on Ionization Measurements	233
7.07 Exposure—The Roentgen	234
7.08 Standard Air Chamber	235
7.09 Practical Ion Chambers—The Thimble Chamber	237
7.10 Effective Atomic Number	241
7.11 Determination of Absorbed Dose in “Free Space”	243
7.12 Determination of Absorbed Dose in a Phantom Using an Exposure Calibrated Ion Chamber	246
7.13 Determination of Absorbed Dose at Energies above 3 MeV	248
7.14 Absorbed Dose in the Neighborhood of an Interface Between Different Materials	258
7.15 Relation Between Energy Fluence and Exposure	261
7.16 Summary of Methods to Determine Absorbed Dose ..	266
 <i>Chapter 8</i> THE QUALITY OF X RAYS (Half-Value Layer)	270
8.01 Quality	270
8.02 Effects of Filters on an X Ray Beam	270
8.03 The Measurement of Half-Value Layer	272
8.04 Equivalent Photon Energy	278
8.05 Measured Spectral Distributions	279

	<i>Page</i>
8.06 Types of Spectral Distribution	281
8.07 Spectral Distributions of Scattered Radiation	284
8.08 Conversion of Exposure to Absorbed Dose	286
 <i>Chapter 9</i> MEASUREMENT OF RADIATION (Instrumentation and Techniques)	 290
9.01 Saturation in Ion Chambers	290
9.02 Calculation of Efficiency of Ion Collection—Pulsed Radiation	293
9.03 Calculation of Efficiency of Ion Collection— Continuous Radiation	295
9.04 Operational Amplifiers	300
9.05 Typical Circuits Using Operational Amplifiers	303
9.06 Practical Devices for Measuring Radiation	306
9.07 Types of Ion Chambers	310
9.08 Solid State Detectors—The Diode	314
9.09 Thermoluminescent Dosimetry (TLD)	317
9.10 Chemical Dosimetry	320
9.11 Film as a Dosimeter	323
9.12 Direct Measurement of Absorbed Dose—The Calorimeter	325
9.13 Summary of Calibration Procedures	330
 <i>Chapter 10</i> THE INTERACTION OF SINGLE BEAMS OF X AND GAMMA RAYS WITH A SCATTERING MEDIUM	 336
10.01 Introduction	336
10.02 Phantoms	336
10.03 Functions Used in Dose Calculations	337
10.04 Tissue-Air Ratio	341
10.05 Backscatter Factor	347
10.06 Percentage Depth Dose	349
10.07 Tissue-Phantom Ratios	356
10.08 Equivalent Squares and Circles for Rectangular and Irregular Fields	356
10.09 Patient Dose Calculations	358
10.10 Tabular Data in the Appendix	362
10.11 Isodose Curves	362
10.12 Comparison of Isodose Curves	367
10.13 Calculation of Dose at any Point	369

	<i>Page</i>
10.14 Lateral Electronic Equilibrium	376
10.15 Determination of Isodose Curves	376
10.16 Depth Dose Distributions for High Energy Electrons and Heavy Particles	377
10.17 Summary	380
 <i>Chapter 11</i> TREATMENT PLANNING—SINGLE BEAMS	 382
11.01 Direct Patient Dose Calculations	382
11.02 Alteration of Isodose Curves by Contour Shape	385
11.03 Bolus and Compensating Filters	389
11.04 Dose at Exit Surface	390
11.05 Dose Corrections for Tissue Inhomogeneities	391
11.06 Wedge Filters	396
11.07 Energy Absorption in Biological Material	397
11.08 Integral Dose—Energy Imparted	402
11.09 Whole Body Irradiation	407
 <i>Chapter 12</i> TREATMENT PLANNING—COMBINATIONS OF BEAMS	 411
12.01 Opposing Pairs of Beams	411
12.02 Combinations of Opposing Pairs	416
12.03 Angled Fields and Wedged Pairs	422
12.04 Three-Field Technique	424
12.05 Beam Direction	426
12.06 Special Fields	432
12.07 Use of CT in Treatment Planning	434
12.08 Rotation Therapy—Tumor Dose Calculations	435
12.09 Rotation Therapy—Isodose Distributions	439
12.10 Comparison of Fixed Field and Rotation Therapy	444
12.11 Treatment Planning—Some General Considerations .	446
12.12 Treatment Planning and Recording	449
 <i>Chapter 13</i> BRACHYTHERAPY—INTERCAVITARY AND INTERSTITIAL SOURCES	 453
13.01 Introduction	453
13.02 Radium and Its Radioactive Series	453
13.03 Activity and Source Specification	455
13.04 Exposure Rate and Dose Rate from Radium and Radon Sources	457

	<i>Page</i>
13.05 Construction and Care of Brachytherapy Sources	458
13.06 Dose Prescription in Brachytherapy Treatments	462
13.07 Radium Isodose Curves	464
13.08 Linear Sources	466
13.09 Interstitial Planar Implants	470
13.10 Volume Implants	477
13.11 Radiographic Examination of Radium Implants	478
13.12 Clinical Examples of Brachytherapy Calculations	482
13.13 Brachytherapy in Gynecology	485
13.14 Special Techniques	490
13.15 Summary	496
<i>Chapter 14</i> NUCLEAR MEDICINE	498
14.01 Introduction	498
14.02 Geiger Counter	498
14.03 The Scintillation Detector	502
14.04 Semiconductor Detector	506
14.05 Statistics of Isotope Counting	507
14.06 Resolving Time and Loss of Counts	510
14.07 Sample Counting—Uptake and Volume Studies	511
14.08 Imaging Using Radioactive Materials	515
14.09 Studies with Radioactive Tracers	520
14.10 Biological and Effective Half-Life	521
14.11 Absorbed Dose Arising from Radionuclides within the Body	524
14.12 Permissible Doses in Nuclear Medicine	530
<i>Chapter 15</i> RADIATION PROTECTION	532
15.01 Introduction	532
15.02 Dose Equivalent	532
15.03 Background Radiation	534
15.04 Tissues at Risk	536
15.05 Protective Barriers	542
15.06 Design Considerations for Protective Barriers	548
15.07 Diagnostic X ray Installations	551
15.08 Protection Against Radiation from Small Sources of Radium, Cobalt, and Cesium	551
15.09 Radiation Surveys	553
15.10 Protection in Radioisotope Departments	554
15.11 Personnel Monitoring	554
15.12 Summary	555

	<i>Page</i>
<i>Chapter 16</i> DIAGNOSTIC RADIOLOGY	557
16.01 Introduction	557
16.02 Primary Radiological Image	558
16.03 Radiographic Images	564
16.04 Quality of an Image	570
16.05 Image Intensifier Tube	573
16.06 Phosphors—Fluorescent Materials	575
16.07 Radiographic Film	579
16.08 Television Techniques	585
16.09 Grids	588
16.10 Focal Spot of X ray Tube	591
16.11 Modulation Transfer Function	597
16.12 Theoretical Determination of MTF for Focal Spot ...	602
16.13 Fourier Transform	608
16.14 MTF of Imaging Systems	613
16.15 Noise and Mottle	616
16.16 Optimization of Imaging Systems	619
16.17 Electrostatic Imaging	624
16.18 Tomography and Stereoradiography	630
16.19 CT Scanning	633
16.20 Mammography	645
16.21 Exposures to Patients	648
16.22 Risks in Diagnostic Radiology	653
16.23 Quality Control	655
16.24 Choice of Equipment	662
16.25 Future Trends	665
 <i>Chapter 17</i> RADIOBIOLOGY	 670
17.01 Introduction	670
17.02 Initial Event—The Passage of the Charged Particles ..	671
17.03 Immediate Radiochemical Effects	673
17.04 Assays for Proliferative Capacity—Survival Curves ...	676
17.05 Mathematical Aspects of Survival Curves	678
17.06 Statistical Nature of Radiation Damage	682
17.07 Normal and Tumor Cells—Therapeutic Ratio	684
17.08 Radiobiological Equivalent (RBE)	685
17.09 Cell Cycle and Radiosensitivity	687
17.10 Fractionation	688
17.11 Isoresponse Curves	691
17.12 The Oxygen Effect	693
17.13 Isoeffect Curves and Nominal Standard Dose (NSD) .	697

Page

17.14	Examples of the Application of Radiobiology to Radiotherapy	701
17.15	Survival of Patients	706
17.16	Effects of High Energy Radiation on Cure Rate	714
17.17	Summary of the Application of Radiobiology to Radiotherapy	717
17.18	Summary of the Application of Physics to Radiology ..	718
<i>Appendices</i>		719
A—BASIC DATA		
	Composition by Weight of Materials	720
1	—Constants, Units, and Conversion Factors	721
2a	—Compton Coefficients for Free Electrons	722
2b	—Energy and Photon Fluence per Roentgen; Specific Gamma Ray Constant	722
3a	—Radiological Properties of Air	723
3b	—Radiological Properties of Water	723
3c	—Radiological Properties of Muscle	724
3d	—Radiological Properties of Bone	724
3e	—Radiological Properties of Fat	725
3f	—Radiological Properties of Polystyrene	725
3g	—Radiological Properties of Lucite	726
3h	—Radiological Properties of Bakelite	726
3i	—Radiological Properties of Lithium Fluoride	727
3j	—Radiological Properties of Ferrous Sulphate	727
4a	—Radiological Properties of Hydrogen	728
4b	—Radiological Properties of Carbon	729
4c	—Radiological Properties of Nitrogen	730
4d	—Radiological Properties of Oxygen	731
4e	—Radiological Properties of Aluminum	732
4f	—Radiological Properties of Calcium	733
4g	—Radiological Properties of Copper	734
4h	—Radiological Properties of Tin	735
4i	—Radiological Properties of Lead	736
5	—Ionizational Stopping Powers	737
6	—Range and Radiation Yield for Electrons	738
7	— f_{med} for various materials	739
B—RADIATION THERAPY DATA		
1a	—Backscatter Factors for Circular Fields	742
1b	—Backscatter Factors for Rectangular Fields	742

	<i>Page</i>
2a—Percent Depth Dose for Circular Fields, HVL 1.0 mm Al	743
2b—Percent Depth Dose for Circular Fields, HVL 3.0 mm Al	743
2c—Percent Depth Dose for Circular Fields, HVL 2.0 mm Cu	744
2d—Percent Depth Dose for Circular Fields, Cobalt 60, SSD 80 cm	744
2e—Percent Depth Dose for Rectangular Fields, Cobalt 60, SSD 80 cm	745
2f—Percent Depth Dose for Square Fields, Cobalt 60, SSD 100 cm	746
2g—Percent Depth Dose for Square Fields, 6 MV x rays, SSD 100 cm	746
2h—Percent Depth Dose for Square Fields, 10 MV x rays, SSD 100 cm	747
2i—Percent Depth Dose for Square Fields, 25 MV x rays, SSD 100 cm	747
3a—Relative Depth Dose for Square Fields, Cobalt 60, SSD 65 cm	748
3b—Relative Depth Dose for Square Fields, 25 MV x rays, SSD 85 cm	748
4a—Tissue Phantom Ratios for Square Fields, Cobalt 60	749
4b—Tissue Phantom Ratios for Square Fields, 24 MV x rays	749
5a—Tissue-Air Ratios for Circular Fields, HVL 1.0 mm Cu	750
5b—Tissue-Air Ratios for Circular Fields, HVL 3.0 mm Cu	750
5c—Tissue-Air Ratios for Circular Fields, Cobalt 60	750
5d—Tissue-Air Ratios for Rectangular Fields, Cobalt 60 ..	751
 C—SCATTER-AIR RATIO DATA	 753
1a—HVL 1.0 mm Al	754
1b—HVL 2.0 mm Cu	754
1c—Cobalt 60 radiation	755
1d—10 MV x rays	756
1e—25 MV x rays	756

	<i>Page</i>
<i>Answers to Problems</i>	757
<i>References</i>	760
<i>Name Index</i>	779
<i>Subject Index</i>	785

THE PHYSICS OF RADIOLOGY

Chapter 1

BASIC CONCEPTS

1.01 INTRODUCTION

The sciences of diagnostic radiology, radiotherapy, radiobiology, and nuclear medicine continue to develop and expand. They are all based on an understanding of the underlying physics. This book is written to help a student interested in any of these fields to understand his science and to help the medical physicist who applies the science of physics to these fields of medicine. In this book we will discuss only those physical principles that are absolutely essential to an understanding of these medical applications. Some of the chapters will be of more interest to physicists than to radiologists. For a first reading of this text, the following guidelines are suggested:

- Physicists should read each chapter in order.
- Diagnostic radiologists should read chapters 1, 2, 3, 5, 15, 16, and parts of 7, 8, 9, 10, and 17.
- Radiotherapists should read chapters 1 to 5, 7 to 13, 15, 17, and parts of 14 and 16.
- Specialists in nuclear medicine should read chapters 1, 2, 3, 5, 14, 15, and parts of 7, 8, 9, and 17.
- Radiobiologists should read chapters 1, 2, 3, 5, 15, 17, and parts of 4, 7, 8, 9, and 14.
- For further study all the chapters should then be read in order.

The availability of pocket calculators has freed scientists of much of the drudgery of handling numerical calculations. Each student should therefore obtain a pocket calculator for his own personal use. It should include exponential functions (e^x and y^x) and the ability to manipulate very large or small numbers using powers of ten.

1.02 QUANTITIES AND UNITS

All meaningful measurements require the statement of a numerical value, which is a pure number, and the unit in which the physical quantity is measured, i.e.,

$$(\text{physical quantity}) = (\text{numerical value}) \times (\text{some unit}) \quad (1-1)$$

For example, one might say the potential across an x ray tube was 80 kilovolts. This involves the pure number 80 and the unit “the kilovolt.”

As each science develops, there is a tendency for each to create its own special units to deal with its own special problems. This has led to confusion when a worker in one field attempts to use work arising from another. In recent years, the Comité International des Poids et Mesures (CIPM) has adopted an international system of units with the abbreviation SI (Système International). These are being officially introduced into most countries of the world.

The International Commission on Radiation Units and Measurements (ICRU) has studied the special problems of units for radiology and has created a number of special units in the past. They now recommend that these special units gradually be phased out and be replaced by SI units. To meet the needs of radiological science, the General Conference of Weights and Measures (CGPM), on the advice of the ICRU, in 1975 established two special SI units, the becquerel and the gray. For further details on these see Wyckoff et al. (W1). In this text we will use the new SI units wherever possible but continually relate these to the earlier ICRU units, which are still in common use.

Fundamental Units

Table 1-1 summarizes some of the important units that are dealt with in this book. Others are introduced as needed. All measurements in science are based on four basic physical quantities: mass, length, time, and electric current. These are shown in the first section of Table 1-1. The corresponding fundamental basic units are the kilogram (kg), the meter (m), the second (s), and the ampere (A), whose *magnitudes* or size are carefully preserved in standardization laboratories throughout the world. They are independent of one another since they represent different ideas and thus cannot be converted from one to another. For example, it would be meaningless to attempt to convert a time in seconds into a length in meters.

Derived Units

The next section of the table introduces a few of the *derived* physical quantities that are relevant to our field. These are based on various combinations of the four fundamental quantities.

Velocity (entry 5) is the ratio of an increment of distance, Δl , to the corresponding increment in time, Δt . It has no special name and can be expressed using *any* unit of distance and *any* unit of time, such as cm per second, meter per second, kilometer per hr, etc. The SI unit of velocity is meter per second (m/s or m s^{-1}).

Acceleration (entry 6) is the ratio of the change in velocity, Δv , to the change in time, Δt , required for this change in velocity. It may be expressed in *any* unit of velocity and *any* unit of time. For example, a car

TABLE 1-1
Fundamental Quantities and Units

	Usual Symbol for Quantity	Defining Equation	SI Unit	Relationships and Special Units
FUNDAMENTAL UNITS				
1 mass	m	Basic physical units	kilogram (kg)	
2 length	<i>l</i>	defined arbitrarily	meter (m)	
3 time	t	and maintained in	second (s)	
4 current	I	standardization laboratories	ampere (A)	
DERIVED UNITS				
5 velocity	v	$v = \Delta l / \Delta t$	m s^{-1}	
6 acceleration	a	$a = \Delta v / \Delta t$	m s^{-2}	
7 force	F	$F = m a$	newton (N)	$1 \text{ N} = 1 \text{ kg m s}^{-2}$
8 work or energy	E	$E = F l = 1/2 m v^2$	joule (J)	$1 \text{ J} = 1 \text{ kg m}^2 \text{ s}^{-2}$
9 power or rate of doing work	P	$P = E/t$	watt (W)	$1 \text{ W} = 1 \text{ J/s}$
10 frequency	f, ν	number per second	hertz (Hz)	$1 \text{ Hz} = 1 \text{ s}^{-1}$
ELECTRICAL UNITS				
11 charge	Q	$Q = I t$	coulomb (C)	$1 \text{ C} = 1 \text{ A s}$
12 potential	V	$V = E/Q$	volt (V)	$1 \text{ V} = 1 \text{ J/C}$
13 capacity	C	$C = Q/V$	farad (F)	$1 \text{ F} = 1 \text{ C/V}$
14 resistance	R	$V = I R$	ohm (Ω)	$1 \Omega = 1 \text{ V/A}$
RADIATION UNITS				
15 absorbed dose	D	energy absorbed from ionizing radia- tion per unit mass	gray (Gy)	$1 \text{ Gy} = 1 \text{ J kg}^{-1}$ $1 \text{ Gy} = 100 \text{ rads}^*$
16 exposure	X	charge liberated by ionizing radiation per unit mass air	C kg^{-1}	roentgen (R)* $1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$
17 activity	A	disintegrations of radioactive material per second	becquerel (Bq)	$1 \text{ Bq} = 1 \text{ s}^{-1}$ $1 \text{ curie}^* (\text{Ci})$ $= 3.7 \times 10^{10} \text{ Bq}$

*The ICRU (W1) recommends that the special units the rad, the roentgen, and the curie be gradually abandoned over the period 1976–1986 and be replaced by the gray (Gy), the coulomb per kg (C/kg), and the becquerel (Bq).

(Useful conversion factors are given in Appendix A-1.)

with a velocity increase of 7.2 km per hour every second would accelerate 7.2 km per hr per second. Acceleration expressed this way involves two different units of time, the hour and the second, and the unit of distance, the km. This acceleration can be expressed in any of the following ways:

$$\begin{aligned}
 a &= 7.2 \frac{\text{km}}{\text{hr}} \times \frac{1}{\text{s}} = 7.2 \times 1000 \frac{\text{m}}{\text{hr}} \times \frac{1}{\text{s}} \\
 &= \frac{7.2 \times 1000 \text{ m}}{3600 \text{ s}} \times \frac{1}{\text{s}} = \frac{2.0 \text{ m}}{\text{s} \times \text{s}} = 2 \text{ m s}^{-2} = 2.0 \text{ m/s}^2
 \end{aligned}$$

It is important that the student understand that numbers (such as 7.2) and units (such as km, hr, etc.) should be carried together in the equation. For example, 1 km is replaced by its equivalent 1000 m. From the above example we see that acceleration involves velocity and time, or distance and time squared. The SI unit of acceleration is meters per s^2 or $m/s^2 = m s^{-2}$. It has no special name.

The next quantity in the table (entry 7) is force, F , for which everyone has an intuitive feeling. If a ball on the level floor starts to move or accelerate, we know that a force has been applied to it. Likewise, if a car suddenly comes to rest or decelerates we know a force has been applied to it. Force is related to acceleration and is defined by Newton's law of motion, which states that $F = m a$. Force is measured by the product of mass and acceleration, and since mass and acceleration are already defined, the unit of force is automatically defined as 1 kg m s^{-2} . This unit of force is so important it is given a special name, the newton:

$$1 \text{ newton} = 1 \text{ N} = 1 \text{ kg m s}^{-2} \quad (1-2)$$

the defining equation is $F = m a$

We now distinguish between mass and force. Suppose you weigh yourself on a hospital balance and obtain the reading 70 kg. This means that you have a mass 70 times the mass of the standard kilogram in Paris. Suppose you now go to the gymnasium and hang from a horizontal bar; what force do you exert on the bar? You know that if the bar breaks you will fall with the acceleration due to gravity of 9.8 m s^{-2} . Hence the pull of the earth on you will give your 70 kg mass an acceleration of 9.8 m s^{-2} and the force exerted by gravity is $F = 70 \text{ kg} \times 9.8 \text{ m s}^{-2} = 686 \text{ kg m s}^{-2} = 686 \text{ newtons}$. Thus, your mass is 70 kg and the force of attraction of the earth for you is 686 newtons. This force varies slightly from place to place on the earth's surface as the acceleration due to gravity changes,* but your mass is constant.

The next quantity is work or energy (entry 8), which is defined as the product of force times distance. Thus, if while hanging from the gym bar you raise your center of gravity 0.50 m, the work done by you against gravity is $686 \text{ N} \times 0.50 \text{ m} = 343 \text{ newton meters} = 343 \text{ N m}$. The newton meter is such an important quantity that it has been given the special name, the joule:

$$1 \text{ joule} = 1 \text{ J} = 1 \text{ newton meter} = 1 \text{ N m} = 1 \text{ kg m}^2 \text{ s}^{-2} \quad (1-3)$$

the defining equation is $E = F l$

It should be emphasized that work in the physical sense described here requires that motion take place. For example, one would get very tired in

*The acceleration due to gravity increases with latitude and decreases with altitude. A few values are Toronto 9.805, London 9.812, North Pole 9.832, Equator 9.780 m s^{-2} .

just hanging from the bar, but one does *not* work until one *raises* oneself.

The next quantity is power (entry 9 in Table 1-1), which is defined as the rate of doing work, or the work done per unit time. The unit of power is the joule per second, but this is so important a unit that it is called a watt:

$$1 \text{ watt} = 1 \text{ W} = \frac{1 \text{ joule}}{1 \text{ second}} = 1 \text{ J/s} = 1 \text{ J s}^{-1} \quad (1-4)$$

the defining equation is $P = E/t = E \text{ t}^{-1}$

A related unit widely used in the English speaking parts of the world is the horsepower, which equals 746 watts.

Frequency (entry 10) is used to describe a repetitive event such as the vibration of a violin string or the oscillations of a crystal. It is simply the number of oscillations per unit time and so has dimensions of $1/\text{second} = \text{s}^{-1}$. This is such an important unit that it is called the hertz.

$$1 \text{ hertz} = 1 \text{ Hz} = 1 \text{ oscillation per second} = \text{s}^{-1} \quad (1-5)$$

Power line frequencies are measured in hertz; on the North American continent, for example, this frequency is usually 60 Hz.

Example 1-1. A young scientist of mass 75 kg at the Ontario Cancer Institute, in a foolish trial of endurance, ran from the basement to the seventh floor (height 25.8 m) in 23.6 s. Calculate the work done and the power developed. In Toronto the acceleration due to gravity is 9.8 m s^{-2} .

Force of attraction of the earth for scientist $F = 75 \text{ kg} \times 9.8 \text{ m s}^{-2} = 735 \text{ newtons}$

Work done $E = 735 \text{ N} \times 25.8 \text{ m} = 19,000 \text{ N m}$
 $= 19000 \text{ joules}$

Power developed $P = \frac{19000 \text{ J}}{23.6 \text{ s}} = 805 \text{ J s}^{-1} = 805 \text{ watts}$
 $= 1.08 \text{ hp}$
 since $746 \text{ watt} = 1 \text{ horsepower}$

This is an impressive development of power. The experiment is not recommended, since the subject was not of much value as a scientist for a few days after the experiment.

Electrical Units

The next section of Table 1-1 involves electrical units (all items involve the fundamental unit of current, the ampere, in combination with other fundamental or derived units). Charge (entry 11) is the product of cur-

rent times time and has dimensions ampere seconds (A s). Because of its fundamental importance it is given a special name, the coulomb:

$$\begin{aligned} 1 \text{ coulomb} &= 1 \text{ C} = 1 \text{ ampere second} = 1 \text{ A s} \\ \text{the defining equation is } Q &= I t \end{aligned} \quad (1-6)$$

Potential, or potential difference (entry 12), is a difficult concept that deals with the electrical pressure that causes a current to flow in a circuit. If we connect a dry cell to a light bulb, a current flows through the bulb producing heat and light. Work is being done by the battery, and the amount of work is proportional to the charge, Q , which passes through the bulb. Potential difference is defined by

$$\text{potential difference} = \frac{\text{work done in electrical circuit}}{\text{charge passing through circuit}} \quad (1-7)$$

Since our unit of work is the joule and unit of charge is the coulomb, potential difference is measured in joules per coulomb. This is such an important unit it is called the volt:

$$1 \text{ volt} = 1 \text{ V} = \frac{1 \text{ joule}}{1 \text{ coulomb}} = 1 \text{ J/C} \quad (1-8)$$

By rearranging equation 1-7 we see that the work done in an electrical circuit is

$$\text{work done} = Q V = I t V \quad (1-9)$$

This leads us to a special unit of energy, the electron volt (eV), which is the energy acquired when an electron of charge $e = 1.602 \times 10^{-19} \text{ C}$ falls through 1 volt. Thus,

$$\begin{aligned} 1 \text{ eV (a unit of energy)} &= 1.602 \times 10^{-19} \text{ C} \times 1 \text{ volt} \\ &= 1.602 \times 10^{-19} \text{ J} \end{aligned} \quad (1-10)$$

$$1 \text{ MeV} = 10^6 \text{ eV} = 10^6 \times 1.602 \times 10^{-19} \text{ J} = 1.602 \times 10^{-13} \text{ J}$$

The electron volt and its multiples are extensively used in radiological science.

Capacity (entry 13) describes the ability of an insulated conductor to store charge. Such an insulated conductor is called a condenser or capacitor. When a charge Q is placed on such a conductor, its potential is raised to V and the capacity C is defined by

$$\text{capacity } C = \frac{\text{charge } Q \text{ stored on conductor}}{\text{potential } V \text{ to which conductor is raised}} \quad (1-11)$$

$$\text{or } Q = C V$$

Since charge is measured in coulombs and potential in volts, the unit of