THE PHYSICS OF RADIOLOGY

FOURTH EDITION

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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.

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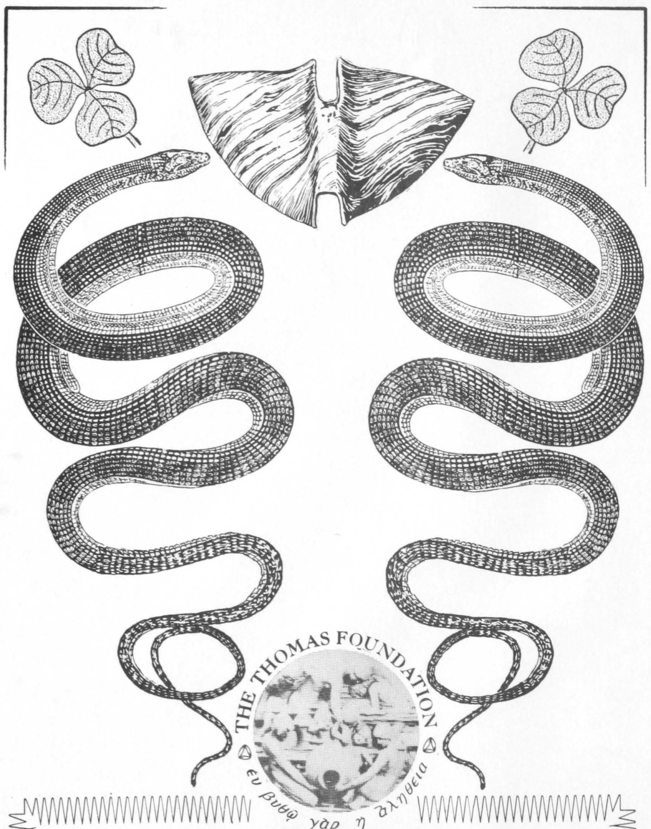

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PREFACE

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

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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.,

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

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 Mésures (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	l	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)	$1\ N = 1\ kg\ m\ s^{-2}$
8 work or energy	E	$E = F\ l = 1/2\ m\ v^2$	joule (J)	$1\ J = 1\ kg\ m^2\ s^{-2}$
9 power or rate of doing work	P	$P = E/t$	watt (W)	1 W = 1 J/s
10 frequency	f,ν	number per second	hertz (Hz)	$1\ Hz = 1\ s^{-1}$
		ELECTRICAL UNITS		
11 charge	Q	$Q = I\ t$	coulomb (C)	1 C = 1 A s
12 potential	V	$V = E/Q$	volt (V)	1 V = 1 J/C
13 capacity	C	$C = Q/V$	farad (F)	1 F = 1 C/V
14 resistance	R	$V = I\ R$	ohm (Ω)	1 Ω = 1 V/A
		RADIATION UNITS		
15 absorbed dose	D	energy absorbed from ionizing radiation per unit mass	gray (Gy)	$1\ Gy = 1\ J\ kg^{-1}$ 1 Gy = 100 rads*
16 exposure	X	charge liberated by ionizing radiation per unit mass air	$C\ kg^{-1}$	roentgen (R)* $1\ R = 2.58 \times 10^{-4}\ C/kg$
17 activity	A	disintegrations of radioactive material per second	becquerel (Bq)	$1\ Bq = 1\ s^{-1}$ 1 curie* (Ci) $= 3.7 \times 10^{10}$ 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:

$$a = 7.2\ \frac{\text{km}}{\text{hr}} \times \frac{1}{\text{s}} = 7.2 \times 1000\ \frac{\text{m}}{\text{hr}} \times \frac{1}{\text{s}}$$

$$= \frac{7.2 \times 1000\ \text{m}}{3600\ \text{s}} \times \frac{1}{\text{s}} = \frac{2.0\ \text{m}}{\text{s} \times \text{s}} = 2\ \text{m s}^{-2} = 2.0\ \text{m/s}^2$$

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:

$$1 \text{ newton} = 1 \text{ N} = 1 \text{ kg m s}^{-2} \qquad (1\text{-}2)$$
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 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 $686 \text{ N} \times 0.50 \text{ m} = 343$ newton meters = 343 N m. The newton meter is such an important quantity that it has been given the special name, the joule:

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

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

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

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/second = s^{-1}. This is such an important unit that is called the hertz.

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

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: $P = \frac{19000 \text{ J}}{23.6 \text{ s}} = 805 \text{ J s}^{-1} = 805 \text{ watts}$

$= 1.08$ hp
since 746 watt = 1 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 current times time and has dimensions ampere seconds (A s). Because of its fundamental importance it is given a special name, the coulomb:

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

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

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

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:

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

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

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

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

$$\mathbf{1\ eV} \text{ (a unit of energy)} = 1.602 \times 10^{-19} \text{ C} \times 1 \text{ volt} \quad (1\text{-}10)$$
$$= \mathbf{1.602 \times 10^{-19}\ J}$$
$$\mathbf{1\ MeV} = 10^6 \text{ eV} = 10^6 \times 1.602 \times 10^{-19} \text{ J} = \mathbf{1.602 \times 10^{-13}\ J}$$

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

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

or $Q = C\ V$

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