THE PHYSICS OF RADIOLOGY

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Fifth Edition

Johns and Cunningham's

THE PHYSICS OF RADIOLOGY

By

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PREFACE

I have yet to see any problem, however complicated, which, when you looked at it in the right way, did not become still more complicated.
Poul W. Anderson, *New Scientist*, 25 September, 1969

Since the publication of the fourth edition of *The Physics of Radiology* in 1983, there has been a phenomenal development in computing technology, which has enabled the rapid development of the imaging techniques of radiology and nuclear medicine, which in turn have enabled the development of radiation oncology and the supporting science of clinical radiobiology. In 1983, the imaging techniques *computed tomography*, *magnetic resonance imaging*, *ultrasound*, *positron emission tomography* and *molecular imaging* were just in their infancy (the latter four techniques do not even get a mention in the fourth edition) and so were radiation oncology and radiobiology (techniques such as *intensity-modulated radiation therapy*, *image-guided radiation therapy*, *stereotactic radiosurgery*, *tomotherapy* and many more were yet to be invented).

We owed a debt of gratitude to Professors Johns and Cunningham long before we agreed to write the fifth edition some seven years ago. We grew up with the fourth edition as our key textbook for radiotherapy physics (though two of us did hone our skills with the third edition in the sixties and seventies!). Subsequently, we all based our lecture courses on this iconic work. To cut a long story short, we would like to convey how the fourth edition was the inspiration behind our respective careers, in that it gave some of the best descriptions of basic radiation physics, the technology and the clinical radiotherapy techniques of the era. We thought what better way to continue the Johns and Cunningham legacy than to write the fifth edition. The publisher gave us few rules, other than to stick to the original format and didactic style of the fourth edition and to keep relevant original text in to provide much-needed continuity.

The basic radiation physics of relevance to clinical oncology, radiology, and nuclear medicine has undergone little change over the last 70 years, so much of the material in the introductory chapters retains the essential flavor of the fourth edition, updated as required. We also considered a name change, possibly to reflect the concentration of this book on the physics and techniques of radiation oncology. Historians (or persons of advanced age) will note that the first edition was entitled *The Physics of Radiation Therapy*. However, the title changed to *The Physics of Radiology* with the expanded second edition, to reflect the importance of, and dependence on, diagnostic radiology and the diagnostic use of radioisotopes (now termed "nuclear medicine imaging"). So, after much discussion, in the end we decided to stick with *The Physics of Radiology*, not only to express continuity with the fourth edition, but also because, as we said above, the *radiation physics* of the three disciplines is essentially the same (albeit with differing emphases); it is the *technology* and *clinical techniques* that have made monumental progress.

In the introduction to Chapter 1 of the fourth edition, Professors Johns and Cunningham advised the different professional groups to concentrate on different chapters, especially on reading the book for the first time. Undoubtedly, some of the chapters will be of more interest to medical physicists than to medical specialists and radiobiologists, but we are not in the fifth edition going to suggest, *ab initio*, different programs of attack for the different professionals with an interest in the subject. We will, however, make some suggestions in some of the chapters as we progress through them.

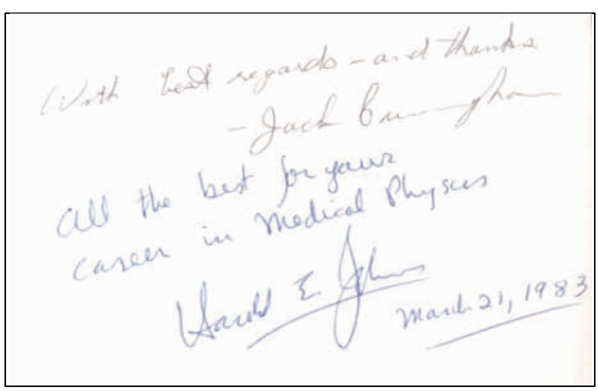
Now a word about the old thorny chestnut of *units*; while the SI unit of absorbed dose (the *gray*) has replaced the *rad* more or less universally, the SI units of *activity* and *exposure* are not so universal, in that the *becquerel* has yet to replace the *curie* and the *coulomb per kilogram* has yet to replace the *roentgen* in all situations, particularly with the latter units (and there are some geographical biases too). Professors Johns and Cunningham, in the preface to the fourth edition, stated the following:

> Committees of the I.C.R.U. are attempting to de-emphasize the use of the *roentgen* as the 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. . . .

While we totally agree with this viewpoint, we have tried hard to continue the transition to SI units by further de-emphasizing the old traditional units in favor of SI (or factors of 10 on SI units, for example, cGy instead of Gy, or MBq instead of Bq, etc.). If the authors of the fourth edition knew that "remnants" of the old units would be still around some 35 years, later they could be excused from expressing their exasperation, but so be it.

Finally, we trust that the practitioners in these fields, be they basic scientists or clinicians, do not heed the words of Poul W Anderson above (*New Scientist*, 25 September, 1969); even complex radiation physics can be stated lucidly and simply. The fourth edition more than amply demonstrates this; we dare to hope that students and practitioners alike will find the fifth edition of *The Physics of Radiology* equally lucid and straightforward.

What better way to finish this preface than with a link to the authors of the fourth edition. Professor Jake Van Dyk of the Department of Medical Biophysics, University of Western Ontario, London, Ontario, Canada, sent us the following image from the inside of his copy of the fourth edition. Professor Van Dyk, as a research student under Professor Johns' tutelage, apparently had been given the task to read the entire type written draft of the 4th edition from cover-to-cover in preparation for the Canadian College of Physicists in Medicine Fellowship exams.



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There are many individuals who have contributed many sections of this text by providing critique, review, advice, expertise, data, figures and permissions. The enthusiastic and generous support of the medical physics and radiation oncology communities was overwhelming. Where appropriate, acknowledgment is provided in the text. We wish to specifically mention the invaluable assistance provided by Ali Asad, Janette Atkinson, Paul Brayshaw, Sebastiaan Breedveld, Sun Chan, Emma Colvill, David Cryer, Simone Culleton, Jason Dowling, Garry Goozzee, Michael Grace, Peter Greer, Garry Grogan, Kristie Harrison, Ben Hug, Joseph Ioppolo, Chris Jones, Angel Kennedy, Ben Khoo, Michelle Krawiec, Jonny Lane, Peter Lanzon, Danny Lee, Peter McLoone, Conor McGarry, Laurence Morandeau, Gabor Neveri, Rik Nezich, Brad Oborn, Hugo Palmans, Harris Panopoulis, Hans Riis, Pejman Rowshan Farzad, Mahsheed Sabet, Rainer Scharli, Alison Scott, Justin Shephard, Yamini Sivashunmugam, John Sutcliffe, David Waterhouse, and Gemma Waters.

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Dedicated to all those employing medical physics and radiopharmaceutical sciences to improve the lives of others.

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THE PHYSICS OF RADIOLOGY

Chapter 1

BASIC CONCEPTS

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1.1 INTRODUCTION

The rapid development of computing technology in the three decades since the publication of the 4th edition has enabled the equally rapid expansion of radiology, radiation oncology, nuclear medicine and radiobiology. The understanding of these clinical disciplines is dependent on an appreciation of the underlying physics. This book is written to help the practitioners in these fields understand the physical science, as well as to serve as a basic tool for physics students who intend working as medical radiation physicists in these clinical fields.

This chapter is, as the title suggests, about the basic concepts. For a graduate physicist, it will just be revision, but for the medically or biologically trained students it will be worth a thorough reading, not only to fill in the background to his/her chosen specialization, but also to appreciate how a physicist thinks.

1.2 QUANTITIES AND UNITS

All measurements require both a numerical value and a meaningful unit in which the physical quantity is measured, such that:

$$\text{Physical quantity} = \text{number} \times \text{unit of measurement}$$

For example, if the potential across an X-ray tube is 80 kV, this involves both the number 80 and the unit, the kilovolt.

As each science develops, there has been a tendency to create specific units and a reader will note that the medical radiation fields are no exception. However, with the universal adoption of the *Système Internationale* (SI) units developed by the *Comité International des Poids et Mésures* based in Paris, France, the older units have been (almost) completely replaced. In particular, the *International Commission on Radiation Units and Measurements* (ICRU) have recommended since the 1970s that the old units be phased out and replaced by SI units. Chief among these were the introduction by the

ICRU in the 1970s of the SI-based units, the becquerel and gray (ICRU 1980). As stated in the Preface, we generally use SI units, but may on occasions have to make mention of older units to explain current practices which still linger on. For example, radiation oncologists tend to use the centigray (cGy), possibly because the cGy is a more conveniently sized unit than the Gy, but more probably because 1 cGy = 1 rad (see Table 1.2).

Table 1.1 lists some of the important units used in this book, but there are others which will be introduced as needed.

All measurements in science are based on seven physical quantities, namely mass, length, time and electric current, luminous intensity, temperature and mole, the first four of which are listed in the table, with their corresponding fundamental SI units, kilogram (kg), meter (m), second (s) and ampere (A). The magnitudes of these units are carefully preserved in metrology (standardization) laboratories in Paris and worldwide.

Table 1.1. Quantities and SI units.

Entity	**Usual symbol**	**Unit type**	**Relationships between entities**	**SI unit**	**Relationship to other SI units**
Mass	m	Fundamental		Kilogram (kg)	
Length	l	Fundamental		Metre (m)	
Time	t	Fundamental		Second (s)	
Current	I	Fundamental		Ampere (A)	
Velocity	v	Derived	$v = \Delta l/\Delta t$	$m \cdot s^{-1}$	
Acceleration	a	Derived	$a = \Delta v/\Delta t$	$m \cdot s^{-2}$	
Force	F	Derived	$F = ma$	Newton (N)	$1\ N = 1\ kg \cdot m \cdot s^{-2}$
Work or energy	E	Derived	$E = Fl$	Joule (J)	$1\ J = 1\ kg \cdot m^2 \cdot s^{-2}$
Power (rate of doing work)	P	Derived	$P = E/t$	Watt (W)	$1\ W = 1\ J \cdot s^{-1}$
Frequency	f	Derived	$f = 1/t$	Hertz (Hz)	$1\ Hz = 1\ s^{-1}$
Charge	Q	Derived	$Q = It$	Coulomb (C)	$1\ C = 1\ A \cdot s$
Potential	V	Derived	$V = E/Q$	Volt (V)	$1\ V = 1\ J \cdot C^{-1}$
Capacity	C	Derived	$C = Q/V$	Farad (F)	$1\ F = 1\ C \cdot V^{-1}$
Resistance	R	Derived	$R = V/I$	Ohm (Ω)	$1\ \Omega = 1\ V \cdot A^{-1}$
*Absorbed dose**	D	Derived	dE/dm	Gray (Gy)	$1\ Gy = 1\ J \cdot kg^{-1}$
*Exposure**	X	Derived	dQ/dm	Coulomb kg^{-1}	
*Activity**	A	Derived	Disintegrations per sec	Becquerel (Bq)	$1\ Bq = 1 \cdot s^{-1}$

* For more detailed explanation, refer to Table 1.2.

The so-called derived quantities/units are all derived from the four fundamental quantities/units listed. For example, *velocity, v*, is the ratio of an increment of distance, Δl, to the corresponding increment in time, Δt, with the SI unit of metre per second ($m \cdot s^{-1}$). Many of the derived units have been given special names; for example, the SI unit of force is called a Newton which is equal to 1 kg·m per second per second ($kg \cdot m \cdot s^{-2}$). Other units can be used; for example, the unit for velocity could be feet per hour, centimetre per year, kilometres per day, depending on the historical context, but it is generally recommended that SI units are used. Conversion between units is frequently required. For example, a car could be increasing its *velocity* (accelerating) by 7.2 km per hour every second. This acceleration could be expressed in the following ways:

$$a = 7.2\,\text{km}\,\text{h}^{-1}\text{s}^{-1} = 7.2 \times 1000\,\text{m}\,\text{h}^{-1}\text{s}^{-1} = \frac{7.2\ \times 1000\,\text{m}}{3600\,\text{s}} \times \frac{1}{\text{s}} = 2.0\,\text{m} \cdot \text{s}^{-2} \tag{1.1}$$

It is important that a student should understand that if conversion between units is required then with each step in the process the relevant numbers must carried forward together. In the above example, 1 km is replaced by 1000 m and 1 h is replaced by 60 × 60 = 3600 s.

1.2.1 Mechanical Quantities and Units

Discussing the other mechanical quantities and units in turn, we first look at *force*. The reader will note that *force* is something which everyone has an intuitive feel for. If a stationary ball on a level floor starts to move, then a *force* has been applied to it. Likewise if a car suddenly slows down (decelerates), we know that a *force* (the brake) has been applied to it. *Force* is related to *acceleration* and is defined by Newton's law of motion, namely $F = ma$. *Force* is measured by the product of *mass* and *acceleration* and since these quantities are already defined the SI unit of *force* is automatically defined as 1 $kg \cdot m \cdot s^{-2}$; as mentioned above this unit of force is given a special name, the *Newton*, such that:

$$1 \text{ newton} = 1 \text{ N} = 1 \text{ kg} \cdot \text{m} \cdot \text{s}^{-2} \tag{1.2}$$

It is important to distinguish between *mass* and *force*. Suppose you weigh yourself on a hospital balance and obtain a reading of 70 kg, which means that you have a *mass* 70 times that of the standard kilogram in Paris. Suppose you now go to the gym and hang from a horizontal bar; what *force* do you exert on the bar? Certainly if the bar breaks you will experience an uncomfortable *acceleration* (downwards) due to gravity of 9.8 $m \cdot s^{-2}$. This implies that the *force* exerted on you by gravity or the *force* exerted on the horizontal bar (before it breaks) is given by $F = 70 \text{ kg} \times 9.8 \text{ m} \cdot \text{s}^{-2} = 686 \text{ kg} \cdot \text{m} \cdot \text{s}^{-2} = 686 \text{ N}$. Your *mass* is 70 kg but the *force* of attraction for you is 686 N, give or take a few newtons, depending on where you are on the Earth.[1]

The next quantity going down Table 1.1 is *work* or *energy* which is the product of *force* and *distance*. Thus to carry on your workout on the horizontal bar if you raise your centre of gravity by 0.5 m, the *work* done by you against the gravity = 686 N × 0.5 m = 343 N·m = 343 N·m = 343 J.

It should be emphasised that while you would get very tired just hanging on the bar, *work* in the physics sense requires motion to take place; that is, one does no *work* until one raises oneself.

The next entity is *power*, which is defined as the rate of doing *work* or *work* done per unit *time*. The SI unit of *power* is joule per second which is named watt:

$$1 \text{ watt} = 1 \text{ W} = \frac{1 \text{ joule}}{1 \text{ second}} = 1 \text{ J s}^{-1} \tag{1.3}$$

The final mechanical quantity in Table 1.1 is frequency, which is simply the number of oscillations or events per unit time and so has dimensions 1/unit time. The SI unit of frequency is known as the hertz, such that:

$$1 \text{ hertz} = 1 \text{ Hz} = 1 \text{ oscillation per second} = \text{s}^{-1}. \tag{1.4}$$

Frequency is fundamental to sound propagation, music, radio waves, microwave ovens and alternating current electricity supply and many other every-day activities.

Example 1.1. A young scientist of mass 75 kg at the Ontario Cancer Institute, in a somewhat foolhardy trial of endurance, ran from the basement to the 7th floor (height 25.8 m) in 23.6 s. Calculate the work done and the power developed. Note that the acceleration due to gravity in Toronto is 9.8 $m \cdot s^{-2}$.

Force of attraction on the scientist,	$F = 75 \text{ kg} \times 9.8 \text{ m} \cdot \text{s}^{-2} = 735 \text{ N}$
Work done,	$W = 735 \text{ N} \times 25.8 \text{ m} = 19{,}000 \text{ J}$
Power developed,	$P = \dfrac{19{,}000 \text{ J}}{23.6 \text{ s}} = 805 \text{ W}$

1. The acceleration due to gravity increases with latitude and decreases with altitude. A few values of the acceleration due to gravity include Toronto 9.805, London 9.812, Los Angeles 9.796, Mexico City 9.779, Sydney (Australia) 9.797, North Pole 9.832, and the Equator 9.780 $m\ s^{-2}$.

1.2.2 Electrical Quantities and Units

Moving on to electrical units in Table 1.1, a student will note that all items involve the fundamental SI unit of electrical *current* in combination with other fundamental or derived units. The first quantity is charge which is simply the product of *current* and *time* (in SI units the ampere·second):

$$1 \text{ coulomb} = 1 \text{ C} = 1 \text{ ampere second} = 1 \text{ A·s} \tag{1.5}$$

The second quantity is *potential* or *potential difference*, which is a slightly more difficult concept and can be thought of as an electrical pressure which causes a current to flow in a circuit. For example, if we connect a battery 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 as the *work*, W, done in an electrical circuit divided by the *charge*, Q, passing through the circuit. In SI units, the *potential difference* is the joule per kilogram, known as a volt:

$$1\,\text{volt} = 1\,\text{V} = \frac{1\,\text{joule}}{1\,\text{coulomb}} = 1\,\text{J}\,\text{C}^{-1} \tag{1.6}$$

By rearranging Equation 1.6, we see that the work done in an electrical circuit is given by:

$$\text{Work done} = W = QV = ItV \tag{1.7}$$

This leads to a very relevant unit applicable to the radiological sciences, namely the electron volt (eV), which is the *energy* acquired when an electron of *charge* e = 1.602×10^{-19} C falls through 1 V. Therefore,

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ C} \times 1 \text{ V} = 1.602 \times 10^{-19} \text{ J} \tag{1.8}$$

or

$$1 \text{ MeV} = 10^6 \text{ eV} = 10^6 \times 1.602 \times 10^{-19} \text{ J} = 1.602 \times 10^{-13} \text{ J} \tag{1.8a}$$

The next quantity in Table 1.1 is *capacity* which 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* is defined as:

$$\text{Capacity}, C = \frac{\text{Charge stored}, Q}{\text{Raised potential}, V} \tag{1.9}$$

or

$$Q = C\,V$$

Since *charge* is measured in coulombs and *potential* in volts, the SI unit of *capacity* is coulombs per volt, known as a *farad*.

$$1\,\text{farad} = \frac{1\,\text{coulomb}}{1\,\text{volt}} = 1\,\text{C}\,\text{V}^{-1} \tag{1.10}$$

Incidentally the farad is an enormous *capacity* and one generally deals with *capacities* of the order of 10^{-6} to 10^{-12} F.

The final electrical quantity listed in Table 1.1 is *resistance*. Suppose a *potential difference*, V, is applied to the ends of a wire causing a *current*, I, to flow in it. The size of the *current* will be proportional to the applied *potential* and will depend on the nature of the wire, namely its *area* and *length* and the material from which it is made. The *resistance* of the wire, R, is defined as the ratio of V to I and so is measured in volt per ampere or ohm (**Ω**):

$$1\,\text{ohm}\,(\Omega) = \frac{1\,\text{volt}}{1\,\text{ampere}} = 1\,\text{V}\,\text{A}^{-1} \tag{1.11}$$