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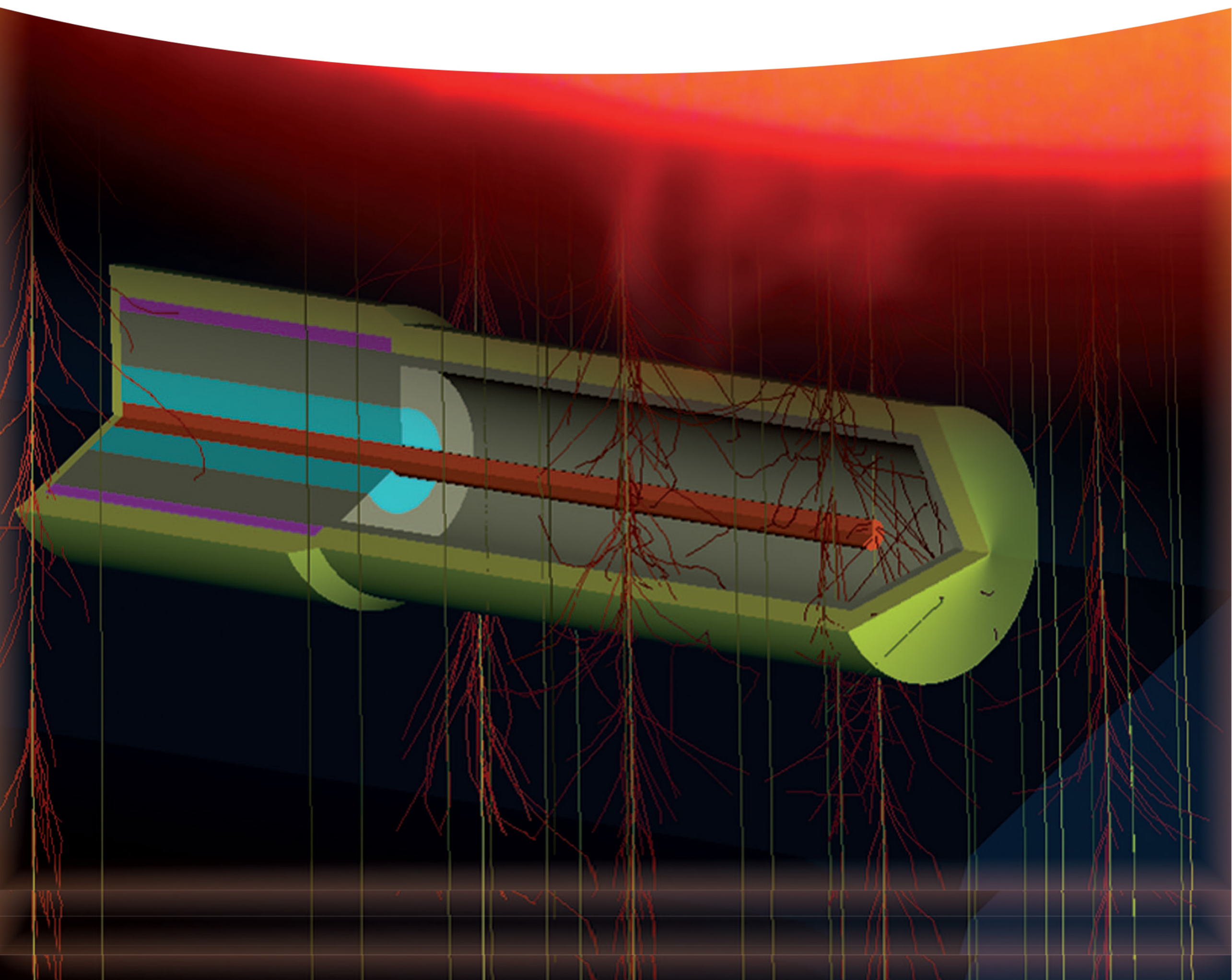

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Contents

Preface

The first edition of Frank Herbert Attix's widely acclaimed book *Introduction to Radiological Physics and Radiation Dosimetry* was published in 1986 and reprinted in 2004. An update of its contents, taking into account the substantial developments in dosimetry in the 30 years since its first appearance, was considered essential. For the present authors it has been a formidable challenge to maintain the high level and quality, raising the former as appropriate, consistent with the current state of knowledge and the various applications. Other recent books of a comparable level are E. B. Podgorsak's *Radiation Physics for Medical Physicists* (Springer, 2010), B. J. McParland's *Nuclear Medicine Radiation Dosimetry – Advanced Theoretical Principles* (Springer, 2010), and N. J. Carron's *An Introduction to the Passage of Energetic Particles through Matter* (Taylor and Francis, 2007).

The scope of this second edition, which we abbreviate to FIORD (from *Fundamentals of IOnizing Radiation Dosimetry*) can be stated as follows: *Given a (ionizing) radiation field from whatever source, be it a radionuclide, an x-ray generator or an accelerator, this book will enable the reader to understand the principles/essentials/fundamentals of the determination of the physical quantity of interest from the interaction of the radiation field with the medium*. In this context, we often refer to absorbed dose as a surrogate of the quantity fluence, although it should be understood that energy transfer from a radiation field can manifest itself in ways other than dose. The text is pitched at senior undergraduate or graduate level, and for the latter a number of advanced topics have been included as addenda to some of the chapters.

We concur with the sentiment expressed by Attix *et al*. (1966) in their edition of the classic text *Radiation Dosimetry*, "Although the present work is called a second edition, it is in many respects a new start." Compared with the first edition, a major change in FIORD is the order of the different chapters; for example, the description of particle interactions with matter (Chapters 2 and 3) is placed before the definition of radiation quantities (Chapter 4). Radiation interactions are covered at a somewhat higher level than that of the first edition, the rationale being the extended use of the Monte Carlo (MC) method (Chapter 8) in radiation dosimetry today, as most MC codes include certain interaction types and details not considered in the majority of books at undergraduate level. More generally, this edition contains everything the student and the practising radiation physicist might need to know about the interactions of radiation with matter in order to understand the theory and practice of radiation dosimetry as covered here. Following the description of the interactions of single particles, Chapters 5 and 6 are devoted to what we choose to call 'macroscopic aspects,' i.e. the interaction of radiation fields and beams with matter. This is followed by the descriptors commonly used to characterize beam quality (Chapter 7), mostly of application in radiation therapy and radiodiagnostics. Cavity theory (Chapter 9) provides the grounds for the theoretical aspects of dosimetry, which is followed by a general overview of radiation detector principles (Chapter 10). The description of the primary measurement standards in current use for the absolute determination of air kerma and absorbed dose (Chapter 11) is followed by separate chapters on the most important types of radiation detectors used for dose determination, namely ionization chambers (Chapter 12), chemical dosimeters (Chapter 13), and solid state detectors (Chapter 14). Practical applications of dosimetry in the different areas are covered in subsequent chapters: reference dosimetry for radiation therapy and dosimetry protocols are dealt with from a general perspective (Chapter 15), complemented by the current status of dosimetry for small and composite photon beams (Chapter 16), which, at the time of writing, is a topic of considerable research. This is followed by the dosimetry of kilovoltage x-ray beams used in diagnostic radiology and interventional procedures (Chapter 17). The dosimetry of radionuclide sources in Chapter 18 follows very closely the original text of the first edition, being complemented by the fundamentals of the dosimetry of unsealed (e.g., for nuclear medicine) and sealed (for brachytherapy) sources. Finally, Chapter 19 provides an update on the dosimetry of neutron beams, nowadays far less frequently employed.

It should be noted that extensive data tables are not provided in the printed edition; the tabulated data are mostly restricted to fundamental constants and data. The reason for this approach is that direct internet access to most of the data needed for numerical calculations, including periodic updates, makes data retrieval more dynamic. For this purpose internet links are provided throughout the various chapters. The most commonly-used practical data, including those less accessible on the web, are however made available via an internet site provided by the editor (http://www.wiley-vch.de/ISBN9783527409211). We consider that the book should not include a compendium of data replacing those in original references. Instead, the use of a large number of figures that provide information on the trends and dependencies of the data has been preferred.

As the book is addressed also to graduate and practising physicists, the authors have opted for the use of in-text citations to references in a style following that of many scientific journals. The large number of 'classic' references given is an attempt to address the apparent shortening of 'scientific historical memory,' resulting in the link to important original sources being progressively lost. Some sections therefore include reviews of certain topics with a sufficient number of references to map the evolution of these topics. The comprehensive list of references makes liberal use of international publications, for example, from the International Commission on Radiation Units and Measurements (ICRU) and the International Atomic Energy Agency (IAEA), in an attempt to provide a global view of radiation dosimetry. This view also justifies the prominent use of internationally accepted symbols for the various quantities.

This second edition is dedicated to the memory of Frank H. Attix, one of the great pioneers in radiation dosimetry and an important contributor to this book. The authors wish to express their gratitude to colleagues who have provided suggestions for improvements to various chapters of the book, in particular F. Ballester, H. Bouchard, D. Emfietzoglou, C. Kessler, B. Mijnheer, J. Perez-Calatayud, F. Salvat, A. Sanchez-Crespo, J. Sempau, and S. Vynckier. Finally, we thank our respective families for their patience and understanding during this seemingly never-ending task.

June 23, 2016

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Quantities and Symbols[1]

Roman letter symbols

A, a

A	atomic mass, mass number (nucleon number)
	distance between the reference plane and the collector of a free-air ionization chamber
$\mathcal{A}$	activity of a radionuclide
$\tilde{\mathcal{A}}$	time-integrated activity (MIRD, formerly called cumulated activity)
$\mathcal{A}_L$	activity per unit length
$\mathcal{A}_{\text{app}}$	apparent activity
$\mathcal{A}_{\text{m}}$	specific (or mass) activity
AF	absorbed-dose fraction (radionuclide point isotropic source)
AF_{m}	specific absorbed-dose fraction
a	surface area

B, b

$\mathbf{B}$	magnetic field vector
B	buildup factor in broad photon beams, also denoted by $B(\mu\ r)$, $B(k, r)$ or $B(k, \theta)$
B_{med}	backscatter factor in kV x-ray beams in medium 'med'
B_{Mol}	Molière's expansion parameter
B_{m}	magnetic field strength
b	impact parameter
	number of bits in the integer representation of computer data (computer word length)

1 Some Roman and Greek symbols that appear with more than one description are used in rather independent sections; thus, there should be no confusion in their meaning. Symbols appearing only once in the text, for example, in a single equation – usually related to a change of variable – or general mathematical functions – for example, the *gamma function* $\Gamma(x)$–have not been included in the list.

C, c

C	electrical capacitance
	cema
C_Δ	restricted cema
$C(\beta)$	shell correction in the stopping-power expression
C_i	concentration of species i (radiation chemistry)
C_K	CT air-kerma index
$C_\mathrm{w,c}$	composite conversion factor in graphite calorimetry
CTDI	CT dose index
c	speed of light in vacuum
c_m	specific heat capacity of a material 'm'
$c_{\mathrm{organ},\mathbf{q}}$	organ dose conversion coefficient calculated for the quantity **q**

D, d

D	absorbed dose
$D_\mathrm{det}, D_\mathrm{med}$	absorbed dose to the radiation-sensitive volume of a detector, or to a medium 'med'
$D_{\mathrm{w},Q}(z)$	absorbed dose to water at a depth z in a beam of quality Q
$D_{\mathrm{pl},Q}(z_\mathrm{eq\text{-}pl})$	absorbed dose to plastic at the equivalent depth $z_\mathrm{eq\text{-}pl}$
D_x	absorbed dose due to a radionuclide disintegration of type x
$\overline{D}$	mean absorbed dose
D_IsoE	isoeffective absorbed dose by protons and heavier charged particles
$D^\mathrm{SSD}(z)$	absorbed dose at depth z with constant SSD ($D^\mathrm{SDD}(z)$ for constant SDD)
$D^\mathrm{field}_{\mathrm{w},Q_\mathrm{field}}$	absorbed dose to water in a specific field
$D_\mathrm{pb}(z, r)$	dose distribution of a pencil beam as a function of depth and radius
$D_\mathrm{bb}(z, R)$	central-axis depth–dose distribution of a broad beam of radius R
$\mathbf{d}$	collision diameter in particle interaction (closest distance of approach)
d	distance (as a generic variable)
	electrode separation in a free-air ionization chamber
d_{80}	depth of the 80% depth dose for a photon beam
$\mathrm{d}\sigma/\mathrm{d}\Omega$	differential cross section per unit solid angle
$\mathrm{d}\sigma/\mathrm{d}E$	differential cross section per energy
$\mathrm{d}\sigma/\mathrm{d}\Omega\ \mathrm{d}E$	double differential cross section, per unit solid angle and per energy
$\%dd(10)$	percent depth dose at a depth of 10 cm (photon beam quality specifier)
$\%dd(10)_\mathrm{x}$	as above, in the absence of electron contamination, that is, filtered by 1 mm Pb

E, e

$\mathbf{E}$	electrical field vector
E	kinetic energy of charged particles

E_{tot}	total energy of charged particles (rest energy plus kinetic energy)
E^+, E^-	positron and electron kinetic energy
E_{a}	kinetic energy of the recoil atom in photon interactions
E_{n}	neutron kinetic energy
E_{trap}	energy depth of TLD trap
$\overline{E}$	mean energy of a spectrum
$\overline{E}_{\Phi}, \overline{E}_{\Psi}, \overline{E}_{K_{\text{air}}}$	mean energy of a spectrum averaged over a fluence, energy fluence, and air-kerma spectrum, respectively
$\overline{E}_z$	mean energy of an electron spectrum at the depth z ($\overline{\text{E}}_0$ at the surface)
E_{abs}	energy absorbed (water calorimetry)
E_{heat}	energy appearing as heat (water calorimetry)
E_{h}	Hartree energy
E_i	mean energy of an i-type particle emitted in a nuclear transition
$E_{\beta_{\text{max}}}$	maximum energy of a beta decay spectrum
$\overline{E}_{\beta}$	mean energy of a beta decay spectrum
E_{p}	plasma energy of a medium (also denoted by $\hbar\omega_{\text{p}}$)
$E(x^n)$	expected value of x, that is, the nth moment of $f(x)$
E/A	specific energy (heavy charged particles)
e	elementary charge, absolute value of the electron charge

F, f

F	atomic form factor
F_{elec}	calibration factor of an electrometer
F_{GS}	Goudsmit–Saunderson angular distribution for multiple elastic scattering
F_{Mol}	Molière's angular distribution for multiple elastic scattering
F_k	fraction of a detector signal produced by photons of energy between k and $k + \text{d}k$
$F(r, \theta)$	anisotropy function for a radioactive line source
$F(x)$	cumulative probability distribution function (CPD)
$F(E, r)$	scaled absorbed dose kernel (radionuclide point isotropic source)
F_{β}	Fermi function in beta decay
f	efficiency of charge collection in an ionization chamber
	enhancement factor of a gas (humid air)
f_d	field size at the distance d (SSD or SDD) in MV photon beams
f_i	oscillator strength of the i-shell of an atom
f_{fel}	free-electron efficiency of charge collection
f_{ref}	conventional broad reference beam (10 cm × 10 cm)
f_{msr}	machine-specific reference (*msr*) field)
f_{pcsr}	plan-class-specific reference (*msr*) field)
$f(Q, W)$	generalized oscillator strength (GOS)
$f(W)$	optical oscillator strength (OOS)
$f(x)$	probability distribution function (PDF) of a continuous variable x
$f_{\text{C}}(Z)$	Coulomb correction factor
$f_{\text{E}}(\beta)$	Elwert factor (in bremsstrahlung)

f_μ detector signal fraction by photons with attenuation coefficient between μ and $\mu + d\mu$
$f_{m,F}$ factor to correct for different radiation interaction coefficients in Fricke dosimetry
$f_{med,det,Q}$ generic cavity-theory factor ($f_{med,det} = D_{med}/D_{det}$) for radiation quality Q

G, g

G chamber geometric factor (recombination in pulsed and continuous radiation)
$G(x)$ radiation chemical yield; related to the G-value
$G(Fe^{3+})$ radiation chemical yield of ferric ions in a Fricke dosimeter
$G_L(r, \theta)$ geometry function for a radioactive line source; $G_P(r)$ for a point source
$\mathcal{G}$ generic quantity
g radiative fraction; related to radiation yield, $Y(E)$
g_e free-electron Landé factor
$g_L(r)$ radial-dose function for a radioactive line source; $g_P(r)$ for a point source

H, h

H Hamiltonian operator
HI homogeneity index of a radiotherapy dose distribution
HVL half-value layer of a kV x-ray spectrum
HVL_1, HVL_2 first and second half-value layers
H_i heat of formation for species i (radiation chemistry)
h relative humidity
h_d heat defect (water calorimetry)
h_i homogeneity index of a kV x-ray spectrum (HVL_1/HVL_2)
$h_{n+\gamma}$ for a neutron detector, response to the photons in a mixed n + γ field relative to its response in a photon calibration beam
h_{ni} for a neutron-insensitive detector, response to the photons in a mixed n + γ field relative to its response in a photon calibration beam
$\dot{h}_T$ TLD heating rate ($K\,s^{-1}$)
$\hbar$ reduced Planck's constant

I, i

I, I_{med} mean excitation energy of a medium (known as the I-value)
I_E first ionization energy of an atom
I_ℓ intensity of a light beam
i ionization current measured by a detector

J, j

$\mathbf{J}$ particle current density (vector fluence rate)
J IA Compton profile

J_{air}	specific charge (charge per unit mass of air)
j	phase-space current density (also termed energy distribution of vector particle radiance, angular current density, or directional flux)

K, k

K	kerma
K_{el}	electronic kerma (also known as collision kerma, K_{col})
K_{rad}	radiative kerma
$K_{air,E}$	air-kerma spectrum or differential air kerma
$K_{air}(t)$	air kerma attenuated by an absorber of thickness t
$[K_{air,Q}]_{med}$	air kerma at the quality Q determined in medium ‘med’
$K_{air,e}$	entrance-surface air kerma
$K_{air,i}$	incident air kerma
$\dot{K}_{air}$	air-kerma rate
$\dot{K}_{R}$	reference-air-kerma rate of a radioactive source
$K_{rel}(\theta)$	correction factor to account for relativistic and spin effects (in σ_{elast})
$K_{scr}(\theta)$	correction factor to account for the screening by atomic electrons (in σ_{elast})
kV	kilovoltage (tube potential), for x-ray spectra produced by electrons with energies in the keV range
$\mathbf{k}$	wave number ($\mathbf{k} = \mathbf{p}/\hbar$)
k	photon energy
$\bar{k}$	mean energy of a photon spectrum
k_{B}	Boltzmann constant
k_{eff}	effective photon energy of a spectrum
k_{max}	maximum photon energy of a spectrum
k_{i}	correction factors for ionization chamber measurements (generic)
k_{a}	correction factor for photon attenuation in a free-air ionization chamber
k_{an}	correction factor for the axial non-uniformity of the electrical field within an ionization chamber
k_{cav}	correction factor for the perturbation of the electron fluence in an ionization chamber
k_{e}	electron-loss correction factor in a free-air ionization chamber
k_{fl}	fluorescence correction factor in a free-air ionization chamber
k_{h}	correction factor for air humidity
k_{hd}	correction factor for heat defect in a water calorimeter
k_{ht}	correction factor for heat transfer in a water calorimeter
$k_{n+\gamma}$	for a neutron detector, response to the neutrons and photons in a mixed n + γ field relative to its response in a photon calibration beam
k_{ni}	for a neutron-insensitive detector, response to the neutrons and photons in a mixed n + γ field relative to its response in a photon calibration beam

k_{p}	perturbation correction factor for non-water materials in a water calorimeter
k_{s}	correction factor for recombination (or saturation)
$k_{\mathrm{s,fel}}$	correction factor for free-electron recombination (or saturation)
k_{sc}	correction factor for photon scattering in a free-air ionization chamber
$k_{\mathrm{th}}^{\mathrm{pp}}$	photon threshold energy for pair production
$k_{\mathrm{th}}^{\mathrm{tp}}$	photon threshold energy for triplet production
k_{wall}	correction factor for photon attenuation and scattering in an ion chamber wall
k_P	correction factor for pressure
k_T	correction factor for temperature
k_+, k_-	mobility of positive and negative ions (recombination in pulsed radiation)
$k_Q^{\mathrm{w,pl}}$	plastic phantom dose conversion factor to water
k_{Q,Q_0}	beam quality correction factor; k_Q if $Q_0 = {}^{60}\mathrm{Co}$ γ rays
$k_{Q_{\mathrm{field}},Q_{\mathrm{ref}}}^{f_{\mathrm{field}},f_{\mathrm{ref}}}$	correction factor to account for the difference between the conventional broad reference beam f_{ref} (10 cm × 10 cm) and the *msr* or the *pcsr* field
$k_{Q_{\mathrm{clin}},Q_{\mathrm{field}}}^{f_{\mathrm{clin}},f_{\mathrm{field}}}$	output correction factor for a beam *clin* relative to the *msr* field or to the *pcsr* field

L, l

$\mathcal{L}$	optical path length in a Fricke dosimeter
L	orbital angular momentum operator
L	length of the region from which charge is measured in a free-air ionization chamber
	length of a radioactive source line
$L(\beta)$	stopping number
$L_\Delta(E)$	linear energy transfer (LET)
$(\bar{L}_\Delta/\rho)_{\mathrm{det}}^{\mathrm{med}}$	Spencer–Attix stopping-power ratio med/det, also denoted by $s_{\mathrm{med,det}}^{\mathrm{SA}}$
l	length, scattering length
ℓ	orbital-angular-momentum quantum number
$\bar{\ell}$	mean chord length of a convex volume

M, m

$\mathcal{M}_{\mathrm{air}}$	molar mass of dry air
$\mathcal{M}_{\mathrm{vap}}$	molar mass of water vapor
M	atomic molar mass
M_{fi}	matrix element of an interaction
$M_{\mathrm{air},Q}$	detector reading in air, corrected for influence quantities, in a beam of quality Q
$M_{\mathrm{w},Q}(z)$	detector reading at a depth z in water, corrected for influence quantities