Nuclear Medicine Radiation Dosimetry

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Advanced Theoretical Principles

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For Sharon

"Doubt thou the stars are fire,
Doubt that the sun doth move,
Doubt truth to be a liar,
But never doubt I love"

- Hamlet Act II, Scene II

Preface

This book addresses the applications of radiation dosimetry theory to diagnostic and therapeutic nuclear medicine, medical disciplines which have both contrasting and parallel requirements.

To begin with, modern medical diagnostic imaging technologies have enabled the visualization of both anatomical structure and function to unprecedented degrees of resolution and complexity. However, with the major exceptions of magnetic resonance, ultrasound, and optical imaging, these technologies require the patient to be exposed to ionizing radiation. This presents the medical practitioner with the challenge of optimizing the diagnostic benefit obtained through the imaging procedure against the theoretical risk posed to the patient as a result of this exposure. The diagnostic benefit of the imaging procedure will be known from prior clinical experience or else have been determined empirically in clinical studies which yield measures of diagnostic efficacy such as sensitivity, specificity, and positive/negative predictive values. Evaluation of the theoretical radiation risk, on the other hand, is much more complex and is based upon the knowledge of the radiation fields and their interactions with tissues in combination with an understanding of the biological consequences of these interactions. The impact of the magnitudes of the risks presented by medical imaging has been the subject of debate for decades as their estimation requires extrapolation of radiation dose responses from epidemiological data obtained at high levels of radiation dose to the lower radiation doses associated with radiological or nuclear medicine procedures.[1] Despite the resulting uncertainty over the magnitudes of these extrapolated and theoretical risks, there is an expectation within modern society to minimize the radiation doses associated with diagnostic medicine whenever practicable. This is not an entirely unfounded or unreasonable expectation. For example, consider the hypothetical case of the informed patient willing to consider trivial an excess cancer mortality risk of 0.5% as a consequence of a particular imaging procedure if the immediate diagnostic benefit to him is overwhelming. On the other hand, society may, indeed should, question the application of

[1]Although, it is now common to see radiation absorbed doses received in modern multislice computed tomography comparable to those received by the survivors of the nuclear bombings at Hiroshima and Nagasaki who still provide the bulk of the epidemiological data of the somatic effects of exposure to ionizing radiation.

an imaging procedure with the same level of risk to the screening of an asymptomatic population of 100,000 individuals, which has the theoretical possibility of inducing 500 extra cancer deaths in that population, and expect that the mortality reduction due to screening exceed the estimated number of extra resulting deaths. Thus, to enable both the clinician deciding upon those imaging tests to be included within this diagnostic process and society to judge the suitability of a broadly-based diagnostic imaging program, means of accurately calculating the radiation doses resulting from imaging procedures are necessary.

Radiological imaging studies involve external beams of radiation and the associated dosimetry evaluations are relatively straightforward as the associated radiation fields can be measured directly and the anatomy irradiated identified simply by the physical alignment of the patient and the radiation beam. As a result, many modern diagnostic radiological devices can provide real-time measures of patient dosimetry through metrics such as the estimated entrance skin dose, dose-area product or Computed Tomography Dose Index. In contrast, the estimation of the patient dosimetry resulting from nuclear medicine procedures is far more complex as the irradiation is internal and is coupled with the combination of the biokinetics of the radiopharmaceutical, the nuclear decay scheme of the radioisotope employed, and the types of radiations emitted during the nuclear decay. The dependence of the internal radiation dosimetry upon the biokinetics makes this dosimetry highly personalized and difficult to predict *a priori*.

The application of radiation dosimetry theory to therapeutic nuclear medicine is markedly different to that applied to diagnosis. In the latter case, the ability to calculate the internal radiation dosimetry is fundamental to the requirements of optimization through estimating and then minimizing the risk presented to the diagnostic nuclear medicine patient. The intent of radiation dosimetry calculation in radionuclide therapy is to improve the chances of cure or palliation by maximizing the therapeutic ratio through maximizing the radiation absorbed dose to the neoplasm of concern and minimizing the absorbed dose to normal uninvolved tissues and the risk of any treatment-related sequelae. In addition to intent, applications of radiobiological theory differ between diagnostic and therapeutic nuclear medicine. In diagnosis (involving low administered activities of a radioisotope), one is concerned with stochastic risks such as radiocarcinogenesis and genetic effects resulting from chromosomal or chromatid aberrations. On the other hand, in therapy (which uses high levels of radioisotope administered activities), one wishes to quantify and understand determinisitic effects such as tumor control and normal tissue radiotoxicity minimization resulting from cell death. Yet, perhaps somewhat surprisingly, quantitative dosimetry applied to nuclear medicine therapy is still relatively infrequent and tends to be based upon empirical and clinical experience. However, the field appears to be entering a renaissance where accurate dosimetry, approaching that required in external beam radiotherapy, may become the norm. Therapeutic applications are, by nature, patient-specific and bespoke calculations are required.

Beyond these two clinical applications of nuclear medicine dosimetry is the need of accurate dosimetry in epidemiological studies of the consequences of radiation exposure. As noted earlier, the bulk of society's understanding of the effects of ionizing radiation upon the human has evolved from the monitoring of the survivors of the nuclear bombings of Hiroshima and Nagasaki. As time progresses and the number of these survivors diminishes, one of the remaining dominant populations of humans providing epidemiological data on the effects of exposure to ionizing radiation will be those patients having been exposed during the course of their diagnosis or therapy. In recent years, the numbers of diagnostic nuclear medicine procedures and the associated absorbed doses have grown immensely. As the epidemiological data are provided in the form of the rate of excess cancer incidence or mortality per absorbed dose, the accurate evaluation of nuclear medicine absorbed doses is essential to the accurate assessment of the risks associated with ionizing radiation.

There are a wide variety of textbooks, monographs, and software available for the practicing nuclear medicine physicist or physician to use in order to estimate the internal radiation dosimetry associated with a given radiopharmaceutical. In fact, one can apply tabular data to estimate the internal radiation dosimetry while being unaware of the assumptions and limitations inherent to the underlying physics and risk estimates. This is quite undesirable. The intent of this book is not to supplant the aforementioned literature; indeed, most (if not all) of this literature is cited here as references. Nor is an intent of this book to provide copious amounts of numerical and physical data: these are already available in the literature, with more recent collections accessible through a large number of Internet sites associated with various national nuclear and physics data centers (and which are also referenced to in this book).

Rather, this book provides the underlying theoretical bases for understanding the many interlocking components of nuclear medicine dosimetry and it is to be considered as an adjunct to these references. To demonstrate this, consider the example of the detailed description of the weak interaction provided in Chap. 4 which includes the development of the Fermi theory to calculate β decay rates and electron and positron energy spectra, allowed and forbidden transitions, the V–A interaction and the nonconservation of parity by weak processes. One could argue that the practicing nuclear medicine physicist does not "need" to know the physics of the weak interaction to this level of detail in order to be able to evaluate internal radiation dosimetry. The counterargument to this view, and that which is taken here, is that β decay, the most commonly observed manifestation of the weak interaction, is fundamental to diagnostic and therapeutic nuclear medicine and the nuclear medicine physicist should have an understanding of the underlying physics of the weak interaction affecting β decay and how this physics is manifested in the dosimetry of a β-emitting radionuclide. Similarly, as the interactions between electromagnetic and corpuscular radiations and matter are at the heart of radiation dosimetry, an understanding of quantum scattering theory is a necessary foundation of any advanced understanding of radiation dosimetry theory. It is somewhat dissatisfying to find that many dosimetry textbooks present, for examples, formulae for the Klein–Nishina cross sections for photon–electron scattering or the Bethe–Heitler cross sections for electron-nuclear *bremsstrahlung* but fail to describe the theoretical development or the limitations inherent to the presented results. It is attempted to address these limitations here by providing, wherever possible, full derivations of those interactions that are at the heart of nuclear medicine dosimetry. However, at the same time, this book attempts to remain as pragmatic wherever possible in describing these derivations by avoiding unnecessary detailed discussions of derivational mechanics (e.g., Dirac trace algebra) when these are both provided adequately elsewhere and exposition would not add value to the dosimetric evaluations provided here.

Necessarily, such results are provided without proof but with cited references for the interested reader to pursue if desired.

As the previous paragraph would suggest, the intended audience of this book is the practicing or research nuclear medicine physicist or graduate student with an interest both in internal radiation dosimetry and, in general, the interactions of radiations with matter at the energies typical of nuclear medicine. This latter audience would include those desiring an in-depth understanding of the underlying physics used, for example, in Monte Carlo simulations of radiation transport at photon and electron/positron energies of about 2 MeV and below and of α particles with kinetic energies of about 10 MeV and below. Hence, the reader is presumed to have had considerable exposure to advanced mathematics, including complex variable theory, and to have a significant understanding of nonrelativistic and relativistic quantum theory in order to fully appreciate the development of the radiation physics that is presented here.

It has been stated that nuclear medicine should be categorized as a "mature" discipline in which all of the underlying scientific principles are known and understood and that only the engineering evolution of the relevant technology is of interest. This assumption is disputed here, at least with regards to the radiation dosimetry. There remains much potential for the applications of fundamental science in this field. As a result, this aspect of the discipline is to be considered far from mature and much fruitful research awaits.

Finally, it is necessary to provide two points – one of clarification and one of defense:

- This book considers only the radiation dosimetry of the patient having received the radionuclide and not that of those individuals exposed to that patient.
- To the possible chagrin of many PET colleagues, this book consolidates PET and single-photon imaging within the single term "diagnostic nuclear medicine" – *mea maxima culpa*.

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During three decades of practice as a medical physicist, I have profited from the intellectual, scholarly, and clinical guidance provided by many teachers and mentors in the physical sciences and the medical arts. It is my hope that this book conveys the combination of scientific rigor, humanity, societal worth, and pure intellectual pleasure of physics applied to medicine that each of them has imparted to me.

The weaknesses that the reader will inevitably find evident in this book would have been far greater had I not been fortunate enough to have benefited from the reviews provided during the course of its writing by colleagues whose expertise span the disciplines of physics, medicine, biology, and pharmacology. I thank (in alphabetical order):

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Glossary and Abbreviations

α	Fine structure constant, $\alpha = e^2/4\pi\varepsilon_0\hbar c \approx 1/37$
	The ^4He nucleus
	Incident photon energy in Compton scatter normalized to the electron mass, $\alpha = {}^{k}/_{m_e}$
	Recombination coefficient
	Townsend coefficient
	Coefficient of linear-quadratic dose response model
α_e	Electronic polarizability
$\alpha\hbar c$	Conversion factor, $\alpha\hbar c = 1.44$ MeV fm
$\boldsymbol{\alpha}_i$	Dirac matrix, $\boldsymbol{\alpha}_i = \begin{pmatrix} 0 & \boldsymbol{\sigma}_i \\ \boldsymbol{\sigma}_i & 0 \end{pmatrix}$
β	Speed normalized to the speed of light, c
	Beta particle (electron or positron) produced through beta decay
	Coefficient of linear-quadratic dose response model
$\boldsymbol{\beta}_i$	Dirac matrix, $\boldsymbol{\beta} = \begin{pmatrix} \mathbf{1} & 0 \\ 0 & -\mathbf{1} \end{pmatrix}$
χ_0	Screening angle for charged particle-atom interactions
χ_a	Molière characteristic screening angle
χ_c	Molière angle
χ_e	Electric susceptibility
δ	Density effect of a medium to the collision stopping power
	Dirac delta function
	δ Particle (recoil electron)
	Multiplication factor per dynode of a photomultiplier tube
Δ^2	$\equiv \hbar^2\partial^2/\partial t^2 - (\hbar c)^2\nabla^2$
ε	Energy imparted
ε_i	Energy deposit for ith single interaction

ε_0	Dielectric permittivity of free space
ε_P	Plating efficiency
ε_R	Relative dielectric constant
ε_{tr}	Energy transferred
$\hat{\varepsilon}$	Photon polarization unit-vector
$\phi(r_T \leftarrow r_S)$	Absorbed fraction for combination of source region r_S and target region r_T
γ	Relativistic contraction factor, $\gamma = 1\big/\sqrt{1-\beta^2}$
	Photon
	Gyromagnetic ratio, $\gamma = \frac{\lvert\boldsymbol{\mu}\rvert}{\lvert\mathbf{L}\rvert}$
$\boldsymbol{\gamma}^0$	Dirac matrix, $\gamma^0 = \boldsymbol{\beta}$
$\gamma^i, i = 1, 2, 3$	Dirac matrix, $\gamma^i \equiv \begin{pmatrix} 0 & \boldsymbol{\sigma}_i \\ -\boldsymbol{\sigma}_i & 0 \end{pmatrix}$ $i = 1, 2, 3$
γ_5	Dirac matrix, $\gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} 0 & \mathbf{1} \\ \mathbf{1} & 0 \end{pmatrix}$
γ_{EM}	Euler-Mascheroni constant
$\Gamma(z)$	Gamma function
Γ_δ	Air kerma rate constant
Φ	Scalar electric potential
	Particle fluence
$\Phi(r_T \leftarrow r_S)$	Specific absorbed fraction for source region r_S and target region r_T
$\boldsymbol{\Phi}$	Vector particle fluence
$d\Phi/_{dt}$	Particle flux density
$d\boldsymbol{\Phi}/_{dt}$	Vector particle flux density
$\hbar$	Reduced Planck constant, $\hbar = h/2\pi$
$\hbar c$	Conversion factor 197.33 MeV fm
φ	Particle flux (particles/cm^2 s)
λ_{Biol}	Biological rate constant
λ_C	Compton wavelength of the electron, $\lambda_C = \frac{h}{m_e c}$
λ_{Eff}	Effective decay constant
λ_{fi}	Transition rate (per unit time) from initial state i to final state f
λ_L	Landau parameter
λ_{LLI}	Clearance constant for lower large intestine contents
λ_{SI}	Clearance constant for small intestine contents
λ_{St}	Clearance constant for stomach contents
λ_{ULI}	Clearance constant for upper large intestine contents
λ_{Phys}	Physical decay constant
λ_{Ruth}	Mean free path between Rutherford scatters
λ_V	Vavilov parameter
$\bar{\lambda}$	Reduced de Broglie wavelength, $\bar{\lambda} = \hbar c/p$
μ	Linear attenuation coefficient
	Mobility
μ/ρ	Mass attenuation coefficient

μ_{en}/ρ	Mass energy-absorption attenuation coefficient
μ_{tr}/ρ	Mass energy-transfer attenuation coefficient
$\mu^{\pm}$	Muon
μ_0	Permeability of free space
μ_{eff}	Effective linear attenuation coefficient
μ_B	Bohr magneton, $\mu_B = e\hbar/2m_e$
μ_N	Nuclear magneton, $\mu_N = e\hbar/2m_p$
μ_d	Deuteron magnetic dipole moment
μ_n	Neutron magnetic dipole moment
μ_p	Proton magnetic dipole moment
$\boldsymbol{\mu}$	Magnetic dipole moment
$\nu_{e,\mu,\tau}$	Neutrino associated with the electron, muon, and tau lepton, respectively
$\aleph$	Dose point kernel
$\pi^{\pm}$, π^0	π-mesons (pions)
$\boldsymbol{\Pi}$	Parity operator
$\Re$	Rate of recombination of positively and negatively charged moieties following ionization in a gas
$\Re(\mathbf{r})$	Radiant energy at position **r**
$\Re_{CSDA}$	Charged particle range in the continuous slowing-down approximation
ρ	Physical density (mass per unit volume)
ρ_e	Electron density (number of electrons per unit volume)
ρ_f	Phase space factor (density of final states per unit energy level)
σ	Total cross section
σ_{KN}	Klein–Nishina total cross section
$\sigma_{KN,S}$	Klein–Nishina scatter cross section
$\sigma_{KN,Tr}$	Klein–Nishina energy-transfer cross section
σ_{PE}	Total cross section for photoelectric absorption
$\sigma_{PE,Tr}$	Energy-transfer total cross section for photoelectric absorption
σ_{Ray}	Total cross section for Rayleigh scatter
σ_{Tho}	Total cross section for Thomson scatter
σ_i; i = 1,2,3	Pauli matrices
$d\sigma/d\Omega$	Differential cross section in solid angle
$d^2\sigma/d\Omega dk'$	Differential cross section in solid angle and scattered photon energy (Compton scatter)
$d\sigma_{Inc}/d\Omega$	Incoherent scatter differential cross section in solid angle
$d\sigma_{KN}/d\Omega$	Klein–Nishina differential cross section in solid angle
$d\sigma_{KN}/dT'_e$	Klein–Nishina differential cross section in electron kinetic energy
$d\sigma_{KN,Tr}/d\Omega$	Klein–Nishina energy-transfer differential across section in solid angle

$d\sigma_{PE}/d\Omega$	Photoelectric absorption differential cross section in solid angle
$d\sigma_{Ray}/d\Omega$	Differential cross section in solid angle for Rayleigh scattering
$d\sigma_{Ruth}/d\Omega$	Differential cross section in solid angle for Rutherford scattering
$d\sigma_{Ruth}/dq$	Differential cross section in three-vector momentum transfer for Rutherford scattering
$d\sigma_{Tho}/d\Omega$	Differential cross section in solid angle for Thomson scattering
$\Im$	Linear scattering power
$\Im/\rho$	Mass scattering power
τ	τ lepton Mean lifetime
$\boldsymbol{\tau}_{\pm}$	Isotopic spin (isospin) ladder operators
ω	Angular frequency
ω_c	Cyclotron frequency
ω_i	Fluorescent yield for orbital i
Ω	Solid angle
Ψ	Logarithmic derivative of the gamma function, Γ Energy fluence
$\boldsymbol{\Psi}$	Vector energy fluence
$d\Psi/dt$	Energy flux density
$d\Psi/dt$	Vector energy flux density
a_i	Auger electron yield for orbital i
A	Atomic mass number Activity
AAPM	American Association of Physicists in Medicine
$A_F(t)$	Activity in voided feces at time t
$A_{Lung,CF}(t)$	Activity in lung space at time t due to activity introduced by a continuous flow generator
$A_{Lung,S}(t)$	Activity in lung space at time t due to activity introduced through rebreathing apparatus
$A_{Lung,Eq}$	Equilibrium lung activity
$A_{LLI}(t)$	Activity in lower large intestine contents at time t
$A_{SI}(t)$	Activity in small intestine contents at time t
$A_{St}(t)$	Activity in stomach contents at time t
$A_{r_S,Norm}(t)$	Activity in source region r_S at time t normalized to that administered
$A_{r_S,Norm,Corr}(t)$	Activity in source region r_S at time t normalized to that administered and corrected for physical decay
$A_{UB,Norm}(t)$	Activity in urinary bladder contents normalized to that administered, at time t

$A_{UBVU,Corr,Norm}(t)$	Activity in urinary bladder contents and voided urine combined, corrected for physical decay and normalized to that at administered, at time t
$A_{ULI}(t)$	Activity in upper large intestine contents at time t
$\mathbf{A}$	Three-vector electromagnetic potential
A_0	Scalar electromagnetic potential
$\tilde{A}_{Lung,Aerosol,Admin}$	Lung administered cumulated activity due to administration via an aerosol
$\tilde{A}_{Lung,CF,Admin}$	Lung administered cumulated activity due to administration via a continuous flow apparatus
$\tilde{A}_{Lung,S,Admin}$	Lung administered cumulated activity due to administration via a rebreathing apparatus
$\tilde{A}_{r_S}$	Cumulated activity in source region r_S
$\tilde{A}_{r_S,\ Norm}$	Cumulated activity in source region r_S normalized to administered activity (also known as the residence time)
$\tilde{A}_F$	Cumulated activity of feces
$\tilde{A}_{LLI}$	Cumulated activity of lower large intestine contents
$\tilde{A}_{RM,Norm}$	Normalized cumulated activity of red bone marrow
$\tilde{A}_{SI}$	Cumulated activity of small intestine contents
$\tilde{A}_{UB,Norm}$	Normalized cumulated activity of the urinary bladder contents
$\tilde{A}_{ULI}$	Cumulated activity of upper large intestine contents
$[\tilde{A}]_{RM,Norm}$	Normalized cumulated activity concentration of red bone marrow
$[A_{BL}(t)]$	Activity concentration in whole blood at time t
$[A(t)]_{BL,Norm,Corr}$	Activity concentration in whole blood, normalized to the administered activity and corrected for physical decay at time t
$[A(t)]_{P,Norm,Corr}$	Activity concentration in plasma, normalized to the administered activity and corrected for physical decay at time t
$[A(t)]_{RM,Norm,Corr}$	Activity concentration in red bone marrow, normalized to the administered activity and corrected for physical decay at time t
$A^{\mu}(\boldsymbol{X}), \boldsymbol{A}_{\mu}(\boldsymbol{X})$	Four-vector electromagnetic potential
ADME	Administration, distribution, metabolism, and excretion
Ai(t)	Airy function, $\mathrm{Ai}(t) = \frac{1}{\pi} \int_0^{\infty} dy \cos\left(yt + \frac{y^3}{3}\right)$
ALARA	As low as reasonably achievable
b	Barn (1b = 10^{-24} cm^2) Impact parameter

becquerel	Unit of activity (transitions per second)
B	Baryon number
	Buildup factor
B(A,Z)	Nuclear binding energy for atomic mass number A and atomic number Z
B_{2k}	Bernoulli number of order 2k
$B_F^{\pm}$	Reduced Fermi transition probability
$B_{GT}^{\pm}$	Reduced Gamow–Teller transition probability
BD	Absorbed dose buildup factor
$B\phi$	Number fluence buildup factor
$B\Psi$	Energy fluence buildup factor
BED	Biologically equivalent dose
BEIR	Biological Effects of Ionising Radiation Panel
B	Magnetic field
Bq	Becquerel
c	Speed of light
cdf	Cumulative density function
cGy	centigray
cpm	Counts per minute
$C_e(\beta)$	Term describing effect of atomic electron shells on collision stopping power
Ci(x)	Cosine integral,
	$\mathrm{Ci}(x) = \gamma_{EM} + \ln x + \int_0^x dt \frac{\cos t - 1}{t}$
CF	Cellularity factor of bone marrow
CFSA	Carrier-free specific activity
CPE	Charged particle equilibrium
CRE	Complete radiation equilibrium
CSDA	Continuous slowing-down approximation
CT	Computed tomography
CZT	Cadmium zinc telluride
dpm	Disintegrations per minute
$d^3\mathbf{r}$	Differential volume element
	$d^3\mathbf{r} \equiv r^2\, dr\, d\varphi\, d(\cos\theta)$
D	Absorbed dose
	Diffusion coefficient
$D_{r_T}(t)$	Absorbed dose at time t in target region, r_T
$D_{r_T,\mathrm{Norm}}(t)$	Absorbed dose at time t in target region, r_T, normalized to the administered activity
D_Q	Quasithreshold absorbed dose
DDREF	Dose and dose-rate effectiveness factor
DSB	Double strand break
DTPA	Diathethylenetriaminepentaacetic acid
eV	Electron volt
E	Total energy (sum of kinetic and rest mass energies)
	Effective dose
E_B	Atomic electron binding energy

$E_{F,p}$	Fermi energy for protons
$E_{F,n}$	Fermi energy for neutrons
EAR	Excess absolute risk
ECMR	Excess cancer mortality rate
ERR	Excess relative risk
$\mathbf{E}_{rad}$	Electric radiation field
$(dE/\rho\, dx)_{Col}$	Collision mass stopping power
$(dE/\rho dx)_{Col,\Delta}$	Restricted collision mass stopping power for electrons or positrons
$(dE/\rho\, dx)_{Col,H}$	Hard-collision mass stopping power
$(dE/\rho dx)_{Col,H,\Delta}$	Restricted hard-collision mass stopping power for electrons or positrons
$(dE/\rho\, dx)_{Col,S}$	Soft-collision mass stopping power
$(dE/\rho\, dx)_{Rad}$	Radiative mass collision stopping power
D	Electric flux density
E	Electric field
$\mathbf{E}_{lm}^{(E)}$	Electric field of electric multipole of order *l*, m
$\mathbf{E}_{lm}^{(M)}$	Electric field of magnetic multipole of order *l*, m
Ei(x)	Exponential integral, $\mathrm{Ei}(x) = \int_{-x}^{\infty} dt\, \frac{e^{-t}}{t}$
e	Fundamental unit of electric charge
$f_n(q, Z)$	Generalized oscillator strength (GOS)
$f_{Self\text{-}atten}$	Self-attenuation correction factor
F	Fano factor
FBP	Filtered backprojection
F(L)	Linear energy transfer (L) frequency distribution
F(q)	Scattering form factor for three-vector momentum transfer, q
F(q,Z)	Atomic form factor
$F(Z_Y,E_e)$	Fermi β-decay nuclear Coulomb correction factor for daughter nucleus Z_Y and β particle energy, E_e
FSU	Functional subunit
f(**q**)	Scattering amplitude as a function of three-vector momentum transfer, **q**
f(A,Z)	Nuclear binding energy per nucleon
ft	Comparative half-life of β decay
g	Gram
	Fraction of liberated charged particles' initial kinetic energies that is irradiated as *bremsstrahlung*
	Marinelli geometric factor
G	Lea–Catcheside dose protraction factor
$G(\mathbf{r}, \mathbf{r}')$	Green's function
GCP	Good clinical practice

Gy	Gray
$h_l^{\binom{1}{2}}(x) = \sqrt{\frac{\pi}{2x}}\left(J_{l+\frac{1}{2}}(x) \pm iN_{l+\frac{1}{2}}(x)\right)$	Hankel functions of first and second type of order l
hcR_∞	Rydberg energy
H	Total Hamiltonian Magnitude of the magnetic field strength
$H_i(x)$	ith Hermite polynomial
H_0	Steady-state Hamiltonian
H_{50,r_T}	Total equivalent dose received by target region r_T over 50 years postexposure
H(t)	Heaviside function: $H(t) = 0 \; t < 0$ $=1 \; t > 0$
H_T	Equivalent dose to tissue or organ T
$H_{EM}(\boldsymbol{X})$	Electromagnetic Hamiltonian
$\mathbf{H}$	Magnetic field strength
$\mathbf{H}_{rad}$	Magnetic radiation field
$\mathbf{H}_{lm}^{(E)}$	Magnetic field of the electric multipole of order l and m
$\mathbf{H}_{lm}^{(M)}$	Magnetic field of the magnetic multipole of order l and m
I	Moment of inertia
IAEA	International Atomic Energy Agency
ICH	International Conference on Harmonisation
ICR	International Congress of Radiology
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurement
IMP	Investigational Medicinal Product
IPEM	Institute of Physics and Engineering in Medicine
I_{ds}	Source-to-drain current in MOSFET
$\bar{I}$	Mean ionization energy/mean excitation potential
$\mathbf{J}$	Total angular momentum Electric current density
$J_l(x)$	Bessel function of the first kind of order l
$j_l(x)$	Spherical Bessel function of the first kind of order l
$J_\mu^{EM}(\boldsymbol{X})$	Four-vector electromagnetic current
$J(p_{e,z})$	Compton profile for electron moment p_e and atom with atomic number Z
k	Photon energy Boltzmann's constant
kVp	Kilovoltage potential
$\mathbf{k}$	Photon three-vector momentum
K	Kerma
K_c	Collision kerma

$K_{c,air}$	In-air collision kerma
$K_\nu(x)$	Modified Besself function of the second kind of order ν
l	Quantum angular momentum number
$l_\mu^C(\boldsymbol{X})$	Weak leptonic current density
L	Total lepton number
L_∞	Unrestricted linear energy transfer
L(β)	Stopping number for charged particle with speed normalized to c, β
LET	Linear energy transfer
LNT	Linear no-threshold (dose response model)
LoR	Line of response
LQ	Linear-quadratic (dose response model)
LT	Linear threshold (dose response model)
L	Total angular momentum
L_e	Electronic lepton number
L_μ	Muonic lepton number
L_τ	Tau lepton number
$Li_n(x)$	Polylogarithm of order n
m_e	Rest mass of the electron
m_μ	Rest mass of the muon
m_n	Rest mass of the neutron
m_N	Reset mass of a nucleon
m_π	Rest mass of the pion (π-meson)
m_p	Rest mass of the proton
m_τ	Rest mass of the tau lepton
mGy	Milligray
M	Multiplication factor (ionization in gases)
M(A,Z)	Atomic mass for atomic mass number A and atomic number Z
M_{fi}	Matrix element, $M_{fi} = \int d^3\mathbf{r}\, \psi_f^* U \psi$, for transition from initial state I to final state f
M_H	Mass of the hydrogen atom
M_{lm}	Magnetic multipole moment of order l,m
MIRD	Medical internal radiation dose
MLEM	Maximum-likelihood expectation maximization
MOSFET	Metal-oxide semiconductor field effect transistor
MR(I)	Magnetic resonance (imaging)
MWPC	Multiwire proportional chamber
n	Neutron
	Principal quantum number
	Index of refraction
N	Number of neutrons in a nucleus, N = A – Z
N_A	Avogadro’s number
$N_l(x)$	Neumann function of order l
NaI(Tl)	Sodium iodide (doped with thallium)

NECR	Noise-equivalent count rate
NTP	Normal temperature and pressure
NURBS	Nonuniform rational B-spline
$\left\langle \frac{dN}{dt} \right\rangle_{geom}$	Geometric mean count rate
OER	Oxygen enhancement ratio
OLINDA/EXM	Organ level internal dose assessment/ exponential modeling
OSEM	Ordered subsets expectation maximization
p	Proton
	Magnitude of three-vector momentum vector, **p**
$p_{T,\ j}$	Spectral distribution of particle radiance for particle species j
pdf	Probability distribution function
$p_{F,p}$	Fermi momentum of protons
$P_{F,n}$	Fermi momentum of neutrons
p	Three-vector momentum
	Electric dipole moment
$\mathbf{p}_T$	Vector particle radiance
p	Four-vector momentum, $\boldsymbol{p} = (E, \mathbf{p})$
P	Pressure
PE	Pulmonary embolism
PET	Positron emission tomography
PI	Product insert
PMT	Photomultiplier tube
P	Poynting vector
	Polarization (number of electric dipole moments per unit volume)
$P_l m(\mu)$	Associated Legendre polynomial of the first kind
$P_l(\mu)$	Legendre polynomial
P_{rad}	Magnitude of the power radiated by an accelerated charged particle
q	Electric charge
	Magnitude of three-vector momentum transfer
Q	Electric charge
	Energy released (>0; exoergic) or absorbed (<0; endoergic) in a transition
	Kinetic energy transfer
	Nuclear electric quadrupole moment
Q_C	Energy transfer demarcating the difference between soft and hard charged-particle collisions
Q/e	Reduced nuclear electric quadrupole moment
Q_{lm}	Electric quadrupole moment of order *l*, m
QE	Quantum efficiency (of a photomultiplier tube)
RE	Relative effectiveness
RR	Relative risk
q	Three-vector momentum transfer

r_S	Source region
r_T	Target region
RBE	Relative biological effectiveness
RIDIC	Radiation Internal Dose Information Center
RM	Red bone marrow
RNG	Random number generator
RoI	Region of interest
$R_{10,50,90}$	Nuclear radius at which the nuclear electric charge density has decreased to 10, 50, and 90%, respectively, of the value at the nuclear center
R_N	Nuclear radius
R_{TF}	Atomic radius in Thomas–Fermi model
R_∞	Rydberg constant
r_0	Classical electron radius, $r_0 = e^2/4\pi\varepsilon_0 m_e c^2$
r_∞	Bohr radius, $r_\infty = \hbar c/\alpha m_e$
s	Intrinsic spin
SCD	Source-collimator distance
$SEE(r_T \leftarrow r_S)$	Specific effective energy from source region r_S to target region r_T (ICRP nomenclature)
SF	Scatter fraction (PET)
	Surviving fraction
SNM	Society of Nuclear Medicine
SPC	Summary of Product Characteristics
SSB	Single strand break (of DNA)
$S(\mathbf{q}, Z)$	Incoherent scattering function
$S(\theta, x)$	Sievert integral, $S(\theta, x) = \int_0^\theta d\theta\, e^{-\frac{x}{\cos\theta}}$
$S(r_T \leftarrow r_S; t)$	S-factor for source region r_S and target region r_T
S_{fi}	S-matrix element for initial state i to final state f
$Si(x)$	Sine integral, $Si(x) = \int_0^x dt\, \frac{\sin t}{t}$
S_n	Neutron separation energy
S_p	Proton separation energy
$S_F(\boldsymbol{X} - \boldsymbol{Y})$	Feynman propagator, $S_F(\boldsymbol{X} - \boldsymbol{Y}) = \frac{1}{(2\pi)^4} \int d^4\boldsymbol{p}\, \frac{e^{-\boldsymbol{p}\bullet(\boldsymbol{X}-\boldsymbol{Y})}}{\not{p} - m}$
SI	Système International
SPECT	Single-photon emission computed tomography
t	Isotopic spin (isospin) vector
t_3	Component of isospin vector in isospin-space
T	Kinetic energy of a particle
T_V	Urinary bladder voiding interval
TCPE	Transient charged particle equilibrium
$TD_{5/5}$, $TD_{50/5}$	Tolerance doses for 5 and 50% complication rates, respectively, in 5 years
TLD	Thermoluminescent dosimetry (dosimeter)
TM	Total trabecular marrow space

$T_{\frac{1}{2}}$	Half life
$T_{\frac{1}{2},Biol}$	Biological half-life
$T_{\frac{1}{2},Eff}$	Effective half-life
$T_{\frac{1}{2},Phys}$	Physical half-life
U_{r_S}	Cumulated activity in source region r_S (ICRP nomenclature)
UV	Ultraviolet
$\mathbf{v}$	Velocity
v	Speed (magnitude of velocity vector)
$\overline{v_d}$	Mean drift speed
V	Electric potential
VoI	Volume of interest
$V_\mu^{C\dagger}(\boldsymbol{X})$	Weak hadronic current density
w_R	Radiation weighting factor
w_T	Tissue weighting factor
W	Mean energy to create an ion pair
$W^\pm$	Charged intermediate vector boson, W
WHO	World Health Organization
WMA	World Medical Association
x	Three-vector position
$\boldsymbol{X}$	Four-vector position
X	Exposure
$\mathbf{X}_{lm}(r, \phi)$	Vector spherical harmonic or order *l*,m
y	Lineal energy
$y_l(x)$	Spherical Bessel function of the second kind of order *l* (also known as a Neumann function)
$Y_l(x)$	Bessel function of the second kind of order *l*
$Y_{lm}(\theta, \phi)$	Spherical harmonic
z	Specific energy (imparted)
Z	Atomic number
Z_{eff}	Effective atomic number
Z_0	Neutral intermediate vector boson