Chapter 2
Dose Quantities and Units for Radiation Protection

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2.1 Introduction

In all fields where there is a need for quantitative measurements, it is necessary to have understandable and precise quantities and units. Practically all countries use the SI system (from French: Le Système International dÚnités). In the field of radiation dosimetry and radiation protection, two other international organisations are active in relation to quantities and units: The International Commission on Radiation Units and Measurements (ICRU), which is mainly working with the physical aspects of dosimetry, and the International Commission on Radiological Protection (ICRP), which mainly works with assessments and quantification of the biological effects of radiation and provides recommendations and guidance on all aspects of radiation protection against ionising radiation.

The goal of the current system of quantities and units is to assess the biological effects resulting from external and internal exposure to ionising radiation in terms of stochastic (cancer induction, genetic effects) as well as deterministic effects (tissue effects) in order to have sufficient mechanisms to control these effects. There are excellent summaries of the evolution of dose quantities and units [1, 2] as well as of the more recent and current situation [3–6].

The present structure of radiation protection quantities and units is complicated and difficult to be readily used in practice, where they may cause some confusion among radiation workers and even among those who are responsible for the regulatory control of occupational radiation exposure at the workplace [7].

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S. Mattsson and C. Hoeschen (eds.), *Radiation Protection in Nuclear Medicine*,
DOI 10.1007/978-3-642-31167-3_2,

The aim of this educational book chapter is to describe dose quantities used in radiation protection, their units and the relations between them. There will also be a discussion on how the currently used quantities and our way to use them could be improved.

2.2 The Basic Dosimetric Quantity

2.2.1 Absorbed Dose

Various dose quantities have been designed by ICRP and ICRU to meet the need to protect human beings (protection quantities) and operational dose quantities which are designed for use in radiation measurements of external irradiation. All dose quantities are based on the fundamental definition of absorbed dose in a point [8] as the quotient of $\mathrm{d}\bar{\varepsilon}$ by $\mathrm{d}m$, where $\mathrm{d}\bar{\varepsilon}$ is the mean energy imparted to matter in an infinitesimal volume $\mathrm{d}V$ at a point of interest in a material of density ρ during a certain period of time by ionising radiation and $\mathrm{d}m$ is the mass in $\mathrm{d}V$. The absorbed dose is defined as

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m}. \tag{2.1}$$

In other words, the nonstochastic quantity absorbed dose is defined as the statistical average of the energy imparted per unit mass at a point. In spite D is a point quantity, it should be recognised that the physical process does not allow $\mathrm{d}m$ to approach zero in the mathematical sense [8]. The unit of absorbed dose is the gray (Gy), and 1 Gy is equal to 1 J/kg.

To illustrate the specific nature of energy absorption when it relates to ionising radiation, it may be of interest to realise that an energy absorption of 280 J in a 70-kg person (which is equivalent to the energy in a sip of hot coffee or tea) gives a mean whole-body absorbed dose of 4 Gy (which is a lethal absorbed dose from ionising radiation).

Absorbed dose can be measured absolutely or relatively using advanced equipment, not at all suitable for daily radiation protection work. In all fields of radiation protection, there is an interest to estimate the risk to the individual or to a group of individuals of the exposure which he/she or they have undergone. Together with the basic quantity absorbed dose, there are two types of quantities defined for specific use in radiological protection: *protection quantities* (defined by the ICRP and used for assessing the exposure limits) and *operational quantities* (defined by the ICRU and intended to provide a reasonable estimate for the protection quantities). How these quantities are related and how they are related to absorbed dose are schematically illustrated in Fig. 2.1 [9]. Information in ICRU Publication 57 [10] facilitates the conversion between operational and protection quantities.

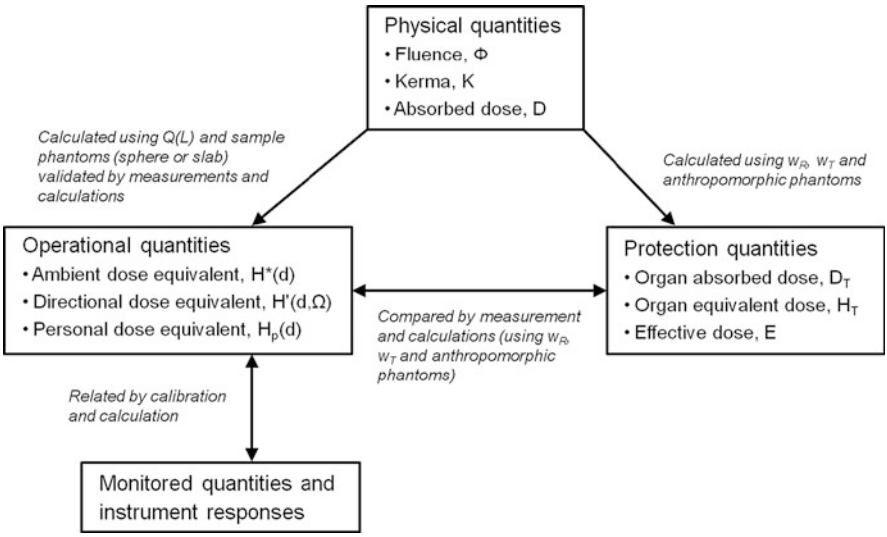

Fig. 2.1 Relationship between physical protection and operational quantities, [9]

2.3 Protection Quantities

A point quantity is not very useful for radiation protection. The average absorbed dose in a given tissue or organ is supposed to be a better indicator of the probability for radiation effects, to assess radiation exposures to humans and other organisms in a quantitative way and to describe dose/response relationships for radiation effects, the basis for risk estimation in radiological protection. This concept is based on the linear dose–effect relationship and the additivity of doses for risk assessment as an appropriate approximation in the low-dose region. Otherwise, averaging of absorbed doses in organs and tissues and adding of doses over long periods would not be an acceptable procedure. Dose distributions that are highly heterogeneous (e.g. DNA precursors labelled with tritium or Auger emitters) may need special treatment.

The protection quantities are *mean absorbed dose* in tissues or organs, *equivalent dose* in tissues or organs, and *effective dose*.

2.3.1 Mean Absorbed Dose

To assess radiation exposure to humans and correlate it with the risk of exposure, mean absorbed dose in tissues or organs is used. The absorbed dose D_T, averaged over the tissue or organ T, is defined as

$$D_{\mathrm{T}} = \frac{\varepsilon_{\mathrm{T}}}{m_{\mathrm{T}}}, \tag{2.2}$$

where ε_{T} is the mean total energy imparted in a tissue or organ T and m_{T} is the mass of that tissue or organ.

2.3.2 Equivalent Dose: Dose Equivalent

Radiation protection would be a very simple indeed if the deleterious effects of ionising radiation were correlated in a very simple way, ideally linearly, with absorbed dose. Unfortunately, the results of a large body of science support the conclusion that these effects are also correlated with the types of particles and their energies.

In 1973, ICRU [11, 12] defined equivalent dose H which is used to take into account the fact that different particle types have biological effects that are enhanced, per given absorbed dose, over those due to the standard reference radiation taken to be 200 keV photons. This quantity has the same physical dimensions as absorbed dose. The SI unit of measure is the sievert (Sv). The concept of equivalent dose is applied only to radiation exposures received by human beings. Equivalent dose is defined as the product of Q and D, where D is the absorbed dose and Q is the quality factor at that point. The dimensionless quality factor Q is dependent on both particle type and energy, and for any radiation field, its value is an average over all components. It is formally defined to have a value of unity for 200 keV photons. In the 1973 system, Q ranges from unity for photons, electrons of most energies and high-energy muons to a value as large as 20 for α-particles (i.e. ^{4}He nuclei) of a few MeV in kinetic energy. For neutrons, Q ranges from 2 to >10 in the 1973 system. Q is defined to be a function of linear energy transfer (LET). LET is the radiation energy lost per unit length of path through a material. Different types of radiation have different LET, and X-rays, gamma rays and electrons are known as low LET radiation. Higher LET is more destructive to biological material than low LET radiation at the same dose. The radiation used in nuclear medicine is typically low LET radiation. LET is approximately equivalent to the stopping power for charged particles and is conventionally expressed in units of keV μm^{-1}. All of the radiation ultimately manifests itself through charged particles, so LET is a good measure of localised radiation damage to materials not limited to biological structures. For the common situation where a spectrum of energies and a mixture of particle types are present, the value of Q for the complete radiation field is an average over the spectrum of LET present weighted by the absorbed dose as a function of LET, D (LET).

ICRP uses radiation weighting factors w_{R} to connect absorbed dose to the protection quantity dose equivalent. The dose equivalent in tissues or organs is defined as

Table 2.1 Radiation weighting factors [6]

Radiation	w_R
Photons, electrons and muons of all energies	1
Neutrons	See Fig. 2.2
Protons >2 MeV (except recoil protons)	2
Alpha particles and heavy ions	20

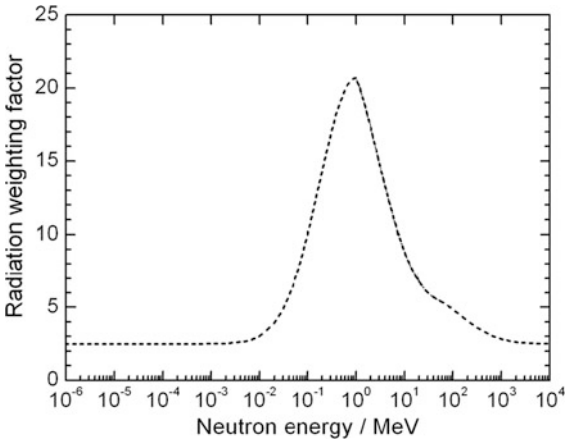

Fig. 2.2 Radiation weighting factors, w_R, for external neutron exposure for neutrons of various energies [6]

$$H_T = \sum_R w_R D_{T,R}. \tag{2.3}$$

The values of the radiation weighting factors w_R are given in Table 2.1. In general, the values of w_R in the 1990 system [9] are larger than those of Q used in the 1973 system. The latest guidance found in ICRP Publication 103 [3] has reduced the size of this increase in w_R for neutrons in some energy intervals (Fig. 2.2).

2.3.3 Effective Dose

The quantity effective dose (originally named effective dose equivalent) was introduced to solve conceptual and practical problems (in particular for internal irradiations) with until then used limitation concept based on “critical organ” and “maximum permissible dose”. ICRP defines effective dose as [6]:

Table 2.2 Organ/tissue weighting factors [6]

Organ/tissue	w_T
Bone marrow, colon, lung, stomach, breast, remainder[a]	0.12
Gonads	0.08
Bladder, liver, oesophagus, thyroid	0.04
Bone surface, skin, brain, salivary glands	0.01

[a]Mean for adrenals, extrathoracic airways, gallbladder, heart, kidneys, lymph nodes, skeletal muscle, oral mucosa, pancreas, SI, spleen, thymus, prostate/uterus–cervix

$$E = \sum_{T} w_T H_T. \tag{2.4}$$

The values of the tissue weighting factors w_T are given in Table 2.2. The concept of "critical organs" could be abandoned as enough knowledge became available to calculate a weighted whole-body dose. The weighting procedure was first described in ICRP Publication 26 [13], but the new quantity was not presented. In a statement from the 1978 Stockholm Meeting of the ICRP [14], the effective dose equivalent was introduced following a proposal by Wolfgang Jacobi. There are a number of assumptions, simplifications and approximations included in the definition of effective dose. It assumes validity of the LNT (linear non-threshold) model in the low-dose range and validity of temporal additivity of dose (committed dose) in the low-dose range.

In 1991, ICRP [5] replaced effective dose equivalent H_E by the effective dose, E. There was no conceptual change compared to $H_{E'}$, but the effective (organ) quality factors were replaced by radiation weighting factors; the number of tissues and organs taken into account was increased, and the values for some tissue weighting factors were modified.

The organ doses that are needed for the calculation of effective dose are calculated for reference male and female persons using a family of *reference phantoms* of which the adult male and the adult female phantom is already published [15] and phantoms for children and newborn are under way.

Using the reference phantoms, *dose conversion coefficients* for external and internal exposure are calculated for *reference conditions*:

- Standard irradiation geometries for external radiations [16]
- Standard (ICRP) biokinetic models for internal emitters, e.g. [17].

Effective dose is *not* based on data from any one individual person and does not provide an individual-specific dose but rather that for a *reference person* under a given exposure situation. Effective dose is therefore, and because of the underlying approximations and simplifications, not suitable for risk assessments for individuals. It is however of practical value for comparing the relative doses related to stochastic effects from different diagnostic examinations, the use of similar technologies and procedures in different hospitals and countries and the use of different technologies for the same medical examination, provided that the representative patients or patient populations for which the effective doses are derived are similar with regard to age and gender.

2.4 Operational Quantities

The human body-related protection quantities, equivalent dose in an organ/tissue and effective dose, are not measurable. To overcome these practical difficulties for external photon irradiation, ICRU [18–20] has introduced and defined a set of *operational quantities*, which can be measured and which are intended to provide a reasonable estimate for the protection quantities. These quantities aim to provide a conservative estimate for the value of the protection quantity avoiding both underestimation and too much overestimation. The operational quantities are based on point doses determined at defined locations in defined phantoms.

One such phantom is the ICRU-sphere [21]. It is a sphere of 30 cm diameter with a density of 1 g/cm^3 and a mass composition of 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen.

For practical calibration work, the ICRU-sphere can be replaced by a square block with the same composition and with the dimensions 30 cm $\times$ 30 cm $\times$ 15 cm.

A single depth in the ICRU-sphere (or square block) has been recommended at which a practical approximation of the effective dose to an adult can be obtained.

For conceptual simplicity and for practicality of measurement, the operational quantities are defined (ICRU Report 39) as point functions [18], i.e. their values at a specified point depend only on the radiation field at this point. Nevertheless, they are related to an extended, remotely anthropomorphic phantom—the ICRU-sphere. To resolve this apparent contradiction, the somewhat artificial concept of an *expanded field* is required; it is the uniform radiation field that agrees with the actual field at the specified point. The principal quantity for area monitoring is, moreover, designed to be independent of the angular distribution of the radiation field, which requires the further abstraction of an *aligned, expanded field*. This is the uniform, unidirectional field that has the same fluence distribution as the expanded field; see Fig. 2.3. Using these two auxiliary concepts, one can define a quantity for the environmental monitoring of penetrating radiation [22, 23].

2.4.1 Ambient Dose Equivalent

The ambient dose equivalent, $H^*(10)$, is the operational quantity for *area monitoring*. It is the dose equivalent at a point in a radiation field that would be produced by the corresponding expanded and aligned field in a 30-cm-diameter sphere of unit density tissue (ICRU-sphere) at a depth of 10 mm on the radius vector opposing the direction of the aligned field. An oriented and expanded radiation field is an idealised radiation field which is expanded and in which the radiation is additionally oriented in one direction. How radiation protection instruments are calibrated in this quantity is described below.

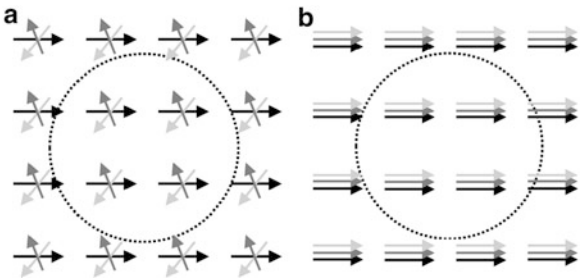

Fig. 2.3 Diagram of an expanded (**a**) and an oriented (**b**) radiation field (after [9])

2.4.2 The Directional Dose Equivalent

The directional dose equivalent, $H'(d, \Omega)$, is the operational quantity for determination of equivalent dose to skin, lens of the eye, etc., also for β-radiation and low-energy photons.

The directional dose equivalent at the point of interest in the actual radiation field is the dose equivalent which would be generated in the associated expanded radiation field at a depth of d mm on the radius of the ICRU-sphere which is oriented in the fixed direction Ω. The point is lying on a radius which has the direction Ω.

In the expanded field, the fluence and its angular and energy distribution have the same values throughout the volume of interest as the actual field at the point of reference. In the aligned and expanded field, the fluence and its energy distribution are the same as in the expanded field, but the fluence is unidirectional. If the dose equivalent in skin is to be determined, the depth 0.07 mm shall be used. If the dose to the lens is to be estimated, a depth of 3 mm might be better, while 10 mm is better for deeper laying organs. The direction can be given as an angle α in relation to a reference direction.

2.4.3 Personal Dose Equivalent

The personal dose equivalent, $H_p(d)$, is the operational quantity for *individual monitoring*: the dose equivalent in soft tissue (ICRU-sphere) below a specified point on the body at an appropriate depth d.

This quantity can be used for measurements of superficial and deep organ doses, depending on the chosen value of the depth in tissue. The depth d is expressed in millimetres, and ICRU recommends that any statement of personal dose equivalent should specify this depth. For superficial organs, depths of 0.07 mm for skin and 3 mm for the lens of the eye are employed, and the personal dose equivalents for those depths are denoted by $H_p(0.07)$ and $H_p(3)$, respectively. For deep organs

and the control of effective dose, a depth of 10 mm is frequently used, with the notation $H_p(10)$.

The personal dose equivalent varies from person to person and from location to location on a person, because of different scattering and attenuation. However, $H_p(d)$ can be assessed indirectly with a thin, tissue equivalent detector that is worn at the surface of the body and covered with an appropriate thickness of tissue equivalent material. ICRU recommends that dosimeters be calibrated under simplified conditions on an appropriate phantom.

2.5 Relationship Between Quantities for Radiological Protection and Monitoring Purposes

The relationship between the physical, protection and operational quantities is illustrated in Fig. 2.4. They are discussed more fully in ICRP [24] Publication 74, which provides conversion coefficients for use in radiological protection against external radiations.

There is an acceptable agreement between the operational and protection quantities for radiation fields of practical significance when the operational quantities are based on the Q/LET relationship given in ICRP Publication 60. In most practical situations, dosimeters provide reasonable approximations to the personal dose equivalent, $H_p(d)$, at least at the location of the dosimeter. When the exposure of the body is relatively low and uniform, it is common practice to enter the dosimeter reading, suitably calibrated, directly into the dose records as a surrogate for effective dose. However, the personal dose equivalent generally overestimates the effective dose.

For many practical situations involving relatively uniform exposure to fairly high-energy gamma radiation, the degree of overestimation is modest; for exposure to low-energy gamma or X-rays, the overestimation can be substantial. For photon energies below ~50 keV, the effective dose can be overestimated by a factor of 2, depending on the orientation of the body.

For exposure to spatially variable radiation fields or where there is partial shielding of the body or extreme variations in the distances of parts of the body from the source, the relationships between the dosimeter measurement and the effective dose are more variable and complex. The practical convention is usually that all quantitative results reported by monitoring services represent the average absorbed dose in the whole body (or the effective dose). It is further assumed that the dose from normal natural background radiation has been subtracted from the reported results. It is also assumed that medical radiation exposures have not been included in the occupational exposure. It is almost always the reading from the dosimeter, suitably modified by calibration factors, that is reported, without considering its relationship to the absorbed doses in the various organs and tissues of the body or to the effective dose. Where exposure of the body is very non-uniform (especially in medical practice) or where exposure

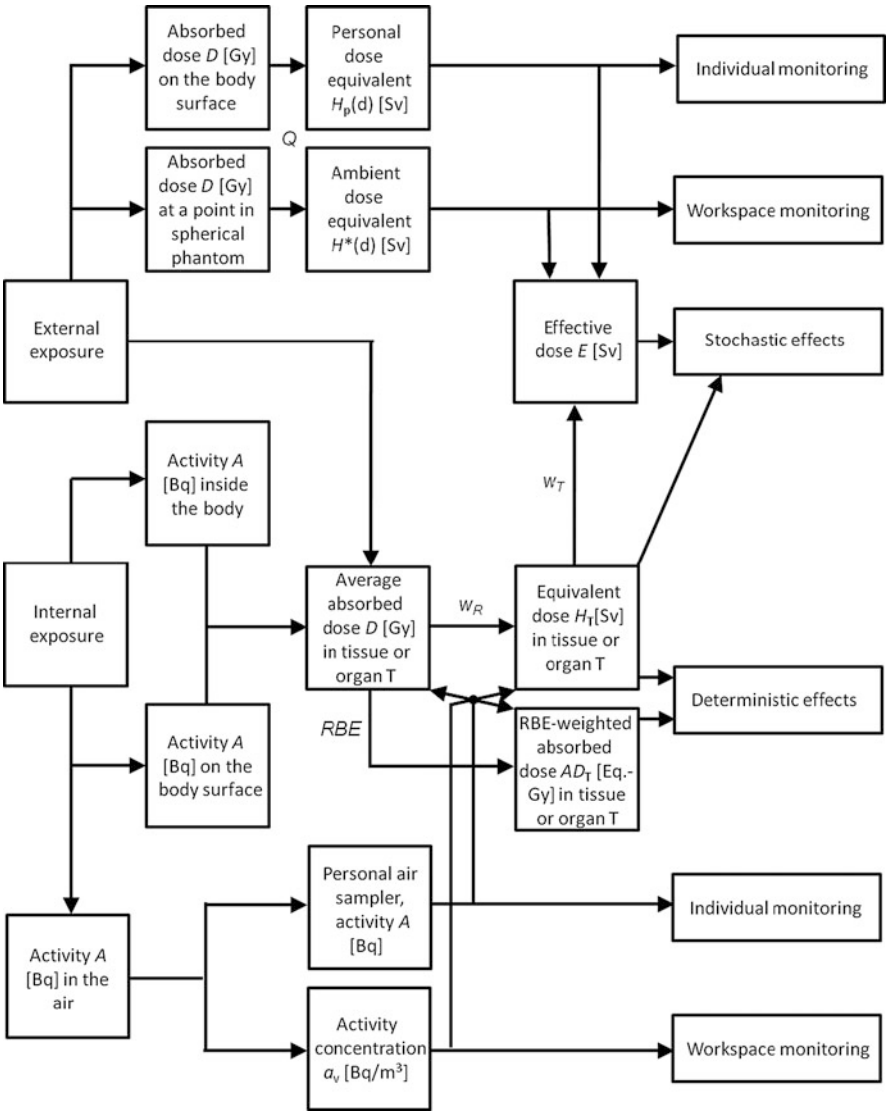

Fig. 2.4 Main quantities used in the present system of radiation protection quantifying the exposure in terms of stochastic as well as deterministic effects due to both external and internal radiation (after [9])

is mainly to low-energy radiation, the use of this convention may result in an overestimate of effective doses, which then needs appropriate qualification.

In the particular case of a unidirectional field, the direction can be specified in terms of the angle α between the radius opposing the incident field and the specified radius.

Table 2.3 The different operational dose quantities and their use (after [6])

	Operational dose quantities	
Task	Area monitoring	Individual monitoring
Estimate of effective dose	Ambient dose equivalent, $H^*(10)$	Personal dose equivalent, $H_p(10)$
Estimate of dose to the skin, hands, feet and to the lens of the eye	Directional dose equivalent, H' (0.07, Ω)	Personal dose equivalent, $H_p(0.07)$

Instruments, which are used to measure ambient dose equivalent, shall have an isotropic response. Instruments, which are used to measure directional dose equivalent and personal dose equivalent, shall have a defined directional response. Examples of detectors that can measure the ambient dose equivalent are ionisation chambers and GM tubes. Also passive detectors, like TLDs, can be used [25].

2.5.1 Calibration Methods

Most individual dosemeters and area monitors are calibrated in terms of the ICRU operational dose quantities for external exposure as part of a legal radiation protection metrology Table 2.3. There are however a number of deficiencies and limitations of the system [26].

There is a problem already in the fact that the ICRU-sphere cannot be fabricated which means that calculated conversion coefficients cannot be experimentally verified. The four-element tissue sphere is not a good phantom when calculating conversion coefficients for neutrons at lower energies. The ICRU-sphere is intended as a simple model for the human body. There are however also a need for the phantoms/models as for extremity monitoring and for the lens of the eye. In fact, there are difficulties with the definition of all three ICRU operational quantities, $H^*(10)$, $H'(0.07)$ and $H_p(d)$.

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