DRAFT FOR DISCUSSION

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION

COMMITTEE 2

BASIS FOR DOSIMETRIC QUANTITIES USED IN RADIOLOGICAL PROTECTION

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Background

For establishing principles and systems of radiological protection, dosimetric quantities are needed in order to assess the radiation exposures of humans as well as other organisms in a quantitative way. The quantification of radiation doses for exposed populations or experimental animals is also important for developing dose-response relationships for radiation effects which are the basis for risk estimation. By extrapolation, such relationships can be used over wider dose ranges than those for which data are available, particularly in the low dose range which is important for radiological protection.

The development of health effects caused by ionising radiation starts with the physical processes of energy absorption in biological tissues, which leads to ionisations with molecular changes which may occur in clusters, e.g. in the genetic information of cells, the DNA in the cell nucleus. Other interactions with cells may also be important in understanding the tissue response to radiation exposure. Such damage includes communication between cells, termed "bystander effect" and may involve the transmission of genomic instability. However, the information on the implications of such responses in terms of the overall tissue effects is unclear at present and it is concluded in the Committee 1 Foundation Document (FD-C-1) that such effects cannot at present be taken into account in dose and risk assessment for protection purposes.

For assessing radiation doses from external radiation exposures and from intakes of radionuclides special dosimetric quantities have been developed by the International Commission on Radiological Protection (ICRP) and by the International Commission on Radiation Units and Measurements (ICRU). The fundamental dosimetric quantities adopted by ICRP are based on measures of the energy imparted to organs and tissues of the human body. A set of such quantities was adopted by ICRP in its 1977 Recommendations and further developed in the 1990 Recommendations. Based on absorbed dose averaged over an organ or tissue these quantities were the equivalent dose, effective dose and the subsidiary quantities committed dose and collective dose (ICRP 1991). These are not quantities that can be measured directly. The protection system therefore also includes operational quantities. ICRU has developed a set of measurable operational dose quantities for exposure to external radiation which have been evaluated by a joint Task Group of the ICRP and the ICRU (ICRP 1996). The analysis by the Task Group indicated that the operational dose quantities recommended by ICRU generally achieve the objective of providing "measurable quantities that adequately represent the protection quantities." For internal exposures following intakes of radionuclides activity quantities in combination with dose coefficients developed by ICRP are also used as operational quantities.

In the light of new scientific data and to make the system of radiological protection more coherent and understandable, ICRP has decided to develop the system further. A Working Group of Committee 2 was asked to prepare a Foundation Document describing the development of the dosimetric quantities to be adopted in the new Recommendations of ICRP.

The following text describes the system and provides some background to its development.

1 Introduction

Exposure of the cells and tissues of the human body to ionising radiations can result in both short term and long term health effects. At high doses acute damage to organs and tissues mainly arises as a result of loss of function involving cell killing and in extreme cases can cause death of the exposed individual. This type of damage is now termed "tissue reactions" by the ICRP having previously been called *non-stochastic* effects in ICRP Publication 26 (1977) and *deterministic effects* in ICRP Publication 60 (1991). At lower doses and at low dose rates these tissue reactions are usually not seen, but damage to the genetic material may occur that can result in an increase in the risk of cancer many years later or hereditary disease in future generations. Such damage continues to be termed *stochastic* as the probability of the effect, but not its severity is assumed to increase with dose.

Radiological protection is concerned with controlling exposures to ionising radiation so that acute damage is prevented and the risk of long term health effects is limited to acceptable levels. The specific *protection quantities* that ICRP has developed for radiological protection allow quantification of the extent of exposure to ionising radiation from both whole and partial body external irradiation and from intakes of radionuclides. They are based upon assessment of the energy imparted to organs and tissues of the body. The estimated doses can then be compared with recommended dose limits for people who are occupationally exposed and for members of the public.

The protection system also includes *operational quantities* used in monitoring and practical applications for investigating situations involving external exposure and intakes of radionuclides.

For demonstrating compliance with exposure limits, there would preferably be one single dosimetric quantity specifying the "amount" of whole or partial body exposure which is quantitatively related to the probability of an effect for all types of radiations, regardless of whether the radiation is incident on the body or emitted by radionuclides within it. This ideal is complicated by variations in the response of organs and tissues to radiations of different quality and by the varying sensitivity to radiation damage of the organs and tissues of the body. These factors influence the response of all members of the population to radiation exposure. They are taken into account in the protection quantities using radiation and tissue weighting factors. Other factors including gender, age and individual sensitivity will influence the individual risk but such biological phenomena are not taken into account for the definition of the dosimetric quantities.

ICRP first introduced a single protection quantity, *effective dose equivalent*, in Publication 26 (1977). This was developed principally for use in occupational exposure although it has been used more broadly for members of the public. It was intended to be used for exposure limitation and risk management at low doses. ICRP further developed this concept in Publication 60 (1991) with the quantity *effective dose*. The underlying principle was to use the *absorbed dose* as the fundamental physical quantity, to average it over specified organs and

tissues and then to apply suitably chosen weighting factors to take account of differences in biological effectiveness of different radiations and the differences in radiation sensitivities of organs and tissues to stochastic health effects.

The development of the effective dose equivalent and subsequently the effective dose quantity has made a very significant contribution to radiological protection as it has enabled doses from external radiation and from intakes of radionuclides to be summed to demonstrate compliance with dose limits.

The effective dose as defined in Publication 60 (ICRP 1991) has been implemented into legislation and regulations in many countries worldwide. It has been shown to provide a practicable approach to the management and limitation of radiation risk in relation to both occupational exposures and to exposures of the general public. The general acceptance of effective dose as well as the demonstration of its practicability since its introduction are important reasons for maintaining it as the central quantity in radiological protection.

There are, however, a number of limitations in the present dosimetry system that need to be addressed. This Foundation Document, prepared by Committee 2 of ICRP, considers the dosimetric quantities developed by ICRP for radiological protection purposes and their place in the new Recommendations.

This Foundation Document provides a detailed description of the ICRP dosimetry system. The health effects resulting from exposures to ionising radiation are summarised in Section 2 and their place in setting and applying protection principles are described. The basis for the development of the new tissue weighting factors, w_T, is summarised although this is considered in more detail in a Foundation Document prepared by Committee 1 of ICRP. Section 3 considers the development of dosimetric quantities and those now adopted in the new Recommendations. It also describes the operational dose quantities developed by ICRU. Section 4 examines tissue and especially radiation weighting factors in more detail, while Section 5 describes the practical application of these dosimetric quantities in radiological protection, including a discussion of situations in which the use of effective dose is, or is not appropriate. Section 6 examines uncertainties and judgements that must be addressed in using these quantities.

2 Health Effects

Radiological protection in the low dose range is primarily concerned with protection against radiation-induced cancer and hereditary disease. These diseases are termed stochastic effects, as they are probabilistic in nature. It is assumed that any exposure is capable of causing an effect, with no threshold. As a consequence it is not possible to prevent their occurrence and exposure limits are set to limit their occurrence to an acceptable frequency and thus to prevent unacceptable levels of risk. As indicated above, ICRP has developed the quantity effective dose to allow doses from external and internal exposure to be assessed on a common basis. In the calculation of effective dose radiation weighting factors, w_R, are used to allow for the varying effectiveness of different radiations and tissue weighting factors, w_T, allow for the variations in radiation sensitivity of different tissues for the induction of stochastic effects.

At doses above about 0.5–1 Gy (low LET radiation; LET: linear energy transfer, see page 16), associated mainly with accident situations, tissue reactions may occur if exposures exceed threshold doses for such health effects. These thresholds vary with the dose rate and with the radiation quality and the extent as well as the severity of the effect increases with increasing dose and dose rate. Tissue reactions must be considered separately from stochastic effects without threshold doses and cannot be addressed within the framework of effective dose and its supporting parameters, w_T and w_R.

2.1 Stochastic Effects

Exposure to ionising radiation, even at low doses may cause damage to the nuclear (genetic) material in cells that can result in the development of radiation-induced cancer many years later, hereditary disease in future generations and some developmental effects under certain conditions (ICRP 2003b). The induction of cancer by low-LET (LET: linear energy transfer, see page 16) radiation has been demonstrated in the dose range of some tens of mGy and higher and it was concluded by UNSCEAR in its 2000 report that *"studies on DNA repair and the cellular/molecular processes of radiation tumorigenesis provide no good reason to assume that there will be a low-dose threshold for the induction of tumours in general".* Radiation-induced hereditary disease has not been demonstrated in human populations but there is substantial evidence from animal studies of heritable damage to germ cells (ova and spermatozoa as well as their precursor cells). For both radiation-induced cancer and hereditary disease it is the probability of the occurrence of the effect, not its severity, that depends upon the dose and they are termed *stochastic effects*. The assumption for radiological protection purposes is that the risk of stochastic effects increases with dose, with no threshold.

The Foundation Document prepared by Committee 1 (ICRP 2005) gives detailed information on the risk of radiation-induced cancer in organs and tissues of the body and on dose response relationships. It is notable that there are significant differences in sensitivity among the organs and tissues of the body. Thus the thyroid in children, the female breast and the bone marrow have a relatively high sensitivity for the induction of solid cancer and leukaemia whereas the muscle and connective tissue have a relatively low sensitivity. For radiological protection purposes a linear no threshold (LNT) dose response is assumed for radiation-induced cancer and hereditary disease.

The Committee 1 Foundation Document also gives information on other *stochastic effects* that may occur following radiation exposure. This includes damage to the vascular tissue of the circulatory system of blood. At present, however, insufficient data are available from groups exposed to radiation to determine any dose response relationships or to use them as a basis for setting dose limits.

A central feature of the recommendations in ICRP Publication 26 (1977) was that the overall risk of stochastic effects at exposures corresponding to the Commission's dose limits should be approximately equal, regardless of the manner of irradiation – whether the body is uniformly or heterogeneously

irradiated from external radiation or from intakes of radionuclides. This was accomplished by first calculating the mean *dose equivalent* to separate organs and tissues. The dose equivalent, H, was defined by

$$H = D\ Q\ N \qquad (2.1)$$

where *D* is the absorbed dose at a point in the specified tissue and *Q* is the *quality factor* for the specific radiation at this point and *N* is the product of all other modifying factors. *H* is then averaged over the organ or tissue considered. The use of quality factors, first used in Publication 6 (ICRP 1964), allowed for the relative effectiveness of different radiations in causing biological effects and could be thought of as the dosimetric analogue of the Relative Biological Effectiveness *(RBE)* of the radiation. Experimental measurements of RBE in cellular studies *in vitro* and in animal studies show that high-LET radiations, including neutrons and alpha particles, cause more damage per unit of absorbed dose than low-LET radiations. The summation of dose equivalents to individual tissues, modified by *weighting factors*, w_T was then termed the *effective dose equivalent,* H_E. The weighting factors, w_T (later termed tissue weighting factors in Publication 60) accounted for the varying radiation sensitivity of tissues to the induction of stochastic effects.

The w_T values recommended by ICRP in Publication 26 were based on the risk of fatal cancer and of serious hereditary disease (Table 1). ICRP Publication 60 (1991) developed this concept further with an extended set of tissue weighting factors based upon more information on radiation effects on tissues and a broader concept of radiation detriment. In addition to assessing the risk of radiation-induced fatal cancer and hereditary disease it also took into account the severity of the disease and the years of life lost in determining total radiation detriment. Radiation detriment then provided the basis for setting revised values of tissue weighting factors, w_T (Table 1). In addition, radiation weighting factors, w_R, replaced quality factors, *Q* in the calculation of the quantities, *equivalent dose,* H_T and *effective dose, E*. The assumption was made that for protection purposes values of w_R can be taken to be independent of the organ or tissue irradiated and w_T values to be independent of radiation quality. No values different from 1 are now recommended by ICRP for the parameter N.

In the new recommendations ICRP has further developed the concept of tissue weighting factors and now bases values of w_T to a large extent on the incidence of radiation-induced cancer rather than on mortality as well as on the risk of hereditary disease (Committee 1 Foundation Document (FD-C-1)). This is now considered to give a more appropriate basis for the assessment of total radiation detriment. The risk of cancer is again adjusted for severity and for years of life lost.

2.2 Tissue Reactions

At doses much higher than the dose limits recommended in the protection system and in accident situations radiation exposures may be sufficient to cause *tissue reactions* (previously termed non-stochastic effects or deterministic

effects). These result from the impairment of the integrity and function of organs and tissues and clinically observable damage occurs above a threshold dose, although the extent of any damage depends upon the absorbed dose and dose rate as well as radiation quality. The expression of injury varies from one tissue or organ to another depending upon cellular radiosensitivity, the function of differentiated cells, cellular composition and cell renewal capacity. Loss of reproductive capacity of cells, the development of fibrotic changes or cell death play a central role in the pathogenesis of most tissue reactions. Some of the most sensitive tissues, with respect to early tissue reactions, are those with rapidly proliferating cell systems including haematopoietic tissue, the cells lining the gastrointestinal tract, the basal cell layer in the skin, and the male germ cells. Late tissue reactions may also depend in part on damage to blood vessels or connective tissue elements that are essential for the functioning of all organs and tissues as well as of the lens of the eye. Such damage can be expressed many months or even years after radiation exposure.

High-LET radiation, as from neutrons and alpha particles, causes more damage per unit of absorbed dose than low-LET radiation. Values of *relative biological effectiveness* (RBE) for tissue reactions for high-LET compared with low-LET radiations were given in ICRP Publication 58 (1989). In general the RBE values were found to be lower for tissue reactions than those for stochastic effects and to vary with the tissue damage described.

The application of values of the radiation weighting factor, w_R, developed from values of RBE for stochastic effects following exposure to high-LET radiations would, therefore, result in an over-estimate of the likely occurrence and severity of any tissue reaction. When assessing radiation exposure for determining the potential for tissue reactions, the mean absorbed dose to the organ or tissue, weighted by an appropriate value of RBE for the biological end point of concern, should therefore be used. These RBE values may differ for different biological endpoints and different tissues or organs. Guidance on appropriate values of the RBE can be obtained in ICRP Publication 58 (1989), NCRP Report No. 104 (1990) and the Committee 1 Foundation Document (FD-C-1).

As a consequence the quantities radiation-weighted dose (see page 13) and effective dose with their unit of special name Sv should not be used in the quantification of doses in situations where tissue reactions are caused. In general, doses should then be given in terms of absorbed dose with the special name for its unit Gy and if high-LET radiations (neutrons or alpha particles) are involved, an RBE-weighted dose, RBE·D (Gy), may be used. Because of the above mentioned possible variation of RBE values to be considered, it is, however, not proposed to define for the unit of such a quantity to be given a special name but rather use the name Gy and to clearly state which RBE value has been applied in a specific situation.

3 Dose Quantities in Radiological Protection

Radiological protection has the general aim of protecting humans and the environment from harm from ionising radiation after external as well as internal exposures. This requires a quantitative description of radiation fields and of the exposure of the human body. Similar considerations apply to protection of other

biological organisms. While radiation fields can be well described by physical quantities such as particle fluence or air kerma free in air, the description of the exposure of humans must also include information about the biokinetics of radionuclides and other parameters of the human body.

A radiation field of a specific type is fully described by the number *N* of particles, their distributions in energy and direction as well as their spatial and temporal distribution. This needs the definition of scalar and vectorial quantities. Definitions of radiation field quantities are given in detail in ICRU Report 60 (1998). While vectorial quantities providing information on directional distributions are mainly applied in radiation transport theory and calculations, scalar quantities like particle fluence or kerma are often used in dosimetric applications.

Radiation field quantities are defined at any point in a radiation field. There are two classes of radiation field quantities referring either to the number of particles, such as fluence and fluence rate, or to the energy transported by them, such as energy fluence. Radiation fields may consist of various types and those field quantities which are based on particle numbers, are always related to a specific type. This is often expressed by adding the particle name to the quantity, e.g. neutron fluence.

The quantity fluence is based on the concept of counting the number of particles incident or passing a small sphere.

The *fluence, Φ,* is the quotient of d*N* by d*a*, where d*N* is the number of particles incident upon a small sphere of cross-sectional area d*a*, thus

$$\Phi = \frac{\mathrm{d}N}{\mathrm{d}a} \qquad (3.1)$$

The fluence is independent of the directional distribution of the particles passing the sphere. In calculations, fluence is often alternatively expressed in terms of the length of trajectories of particles passing a small volume d*V*. The fluence, *Φ*, is then given by

$$\Phi = \frac{\mathrm{d}l}{\mathrm{d}V} \qquad (3.2)$$

where d*l* is the sum of the lengths of trajectories through this volume d*V*.

While in a radiation field the number of particles traversing a small sphere is always subject to random fluctuations (stochastic process), the fluence - as well as related quantities - is defined to be a non-stochastic quantity which results in a single value at a given point and time with no inherent fluctuation. Its value should be considered as an expectation value.

While *fluence* is an important quantity in describing radiation fields it is not really appropriate and simple enough for general use in radiological protection and the definition of limits, because fluence always needs the additional specification of the particle and the particle energy and its correlation with detriments is complex. Also directional fluence distributions are important.

As mentioned before, in radiological protection practice, one would, in principle, prefer to deal with a single quantity specifying the "amount" of exposure which is quantitatively related to the probability of stochastic effects in human bodies for all types of radiations regardless of which type of ionising radiation is considered or whether the radiation is incident on the body or emitted by radionuclides within the body.

The initial step in the interaction of ionising radiation with biological material is energy absorption that causes ionisations. Thus it might appear reasonable to use the amount of absorbed energy per unit of mass (absorbed dose) as the only term for quantifying the radiation exposure in radiological protection in order to estimate the risk caused by a given exposure. This is not valid, however, as radiation effects depend not only on the absorbed dose but also on the type of radiation, on the distribution of energy absorption in time and space within the human body and on the radiosensitivity of the exposed tissues or organs.

A concept of body related dose quantities was introduced in ICRP Publication 26 (1977) with the quantity effective dose equivalent. This was further developed in Publication 60 (1991) with the quantity *effective dose*. The basic procedure adopted by ICRP is to use *absorbed dose* as the fundamental physical quantity, to average the absorbed dose over specified organs and tissues and to apply suitably chosen weighting factors to take account of differences in biological effectiveness of different radiations and of differences in sensitivities of organs and tissues to stochastic health effects. *Effective dose* may therefore be seen as a quantity based on the radiation field and the primary physical interactions in human tissues as well as on judgements about the biological reactions resulting in stochastic health effects.

The basis and limitations of this concept and of the dose quantities used in radiological protection are described below (see Section 5.3).

3.1 Absorbed Dose

In radiation biology, radiology and radiological protection the absorbed dose, D, is the basic physical quantity. It is used for all types of ionising radiation and any irradiation geometry.

Absorbed dose, D, is defined as the quotient of mean energy , $d\bar{\varepsilon}$, imparted by ionising radiation in a volume element and the mass, dm, of the matter in that volume, that is

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m} \tag{3.3}$$

The SI unit is J kg^{-1} and the special name is gray (Gy). Absorbed dose is derived from the mean value of the stochastic quantity of energy imparted and therefore does not reflect the random fluctuations of the interaction events in tissue. It is defined at any point in matter and, in principle, is a measurable quantity. Primary standards exist to determine the absorbed dose experimentally or by computation. The definition of absorbed dose has the

scientific rigour required for a basic physical quantity. It implicitly takes account of the radiation field as well as of all of its interactions with matter inside and outside the specified volume. It does not, however, take account of the atomic structure of matter and the stochastic nature of the interactions.

A particular feature of ionising radiations is their discontinuous interaction with matter and the related stochastic nature of energy deposition. Energy is transferred to tissue by charged particles in interactions with individual atoms and molecules. The human body is structured in terms of organs, tissues, cells, sub-cellular structures and macromolecules such as DNA. Absorbed dose is defined as the mean of the stochastic distribution of energy deposited in a volume element. The fluctuations of energy deposited in individual cells and sub-cellular structures and the microscopic tracks of charged particles are the subject of *microdosimetry*.

The magnitude of the fluctuations of energy deposited in different small tissue volumes depends on the value of the absorbed dose, on the size of the volume considered and, at a given dose, these fluctuations increase with increasing ionisation density in charged particle tracks (linear energy transfer, LET) of the radiation. At the low absorbed doses generally of concern in radiological protection, the fluctuation of energy deposited can be substantial between individual cells and within a single hit cell. This is the case particularly for densely ionising radiations (high-LET) such as alpha-particles and secondary-charged particles from neutron interactions.

At a given absorbed dose, the actual value of energy imparted, ε, in a small tissue volume, e. g. in a cell, is given by the sum of energies deposited in that volume by all individual events. In any volume, fluctuations of ε are caused by variation in the number of events and by variation in the energy deposited in each event. For low-LET radiations (e. g. photons and electrons) the energy imparted in each event is relatively low and at low doses more cells experience energy deposition events than in the case of exposure to high-LET radiation at the same dose. As a consequence, the fluctuation in the energy deposited among cells is smaller for low-LET than for high-LET radiation.

For low mean doses of high-LET radiation (e. g. charged particles from neutron interactions or alpha-particles) and Auger electrons, the frequency of events in most cells is zero, in a few it is one and extremely exceptionally more than one. The value of energy deposited in most individual cells is then zero but in the "hit" cells it can exceed the mean value (i.e. absorbed dose) in the tissue by orders of magnitude. Even among the hit cells the distribution of these events is very heterogeneous. These large differences in the energy deposition distribution in microscopic regions for different types (and energies) of radiation have been correlated to observed differences in biological effectiveness or radiation quality. Further information is given , for example, in the UNSCEAR 1993 and 2000 reports.

In the definition of radiological protection quantities no attempts are made to specify these stochastic distributions of physical processes at a microscopic level. Instead of explicitly considering such distribution functions, a pragmatic and empirical approach has been adopted to take account of radiation quality differences. Radiation weighting factors and the quality factors are used to take

account of the differences in distributions of energy deposited in microscopic regions through judgements based on the results of radiobiological experiments and information on track structure. This is discussed in more detail in Section 4.1.

3.2 Averaging of Dose

Absorbed dose is defined to give a specific value at any point in matter. However, averaging of doses over larger tissue volumes and integration over time is often performed when using the quantity absorbed dose in practical applications. It is thus assumed that for low doses the resulting mean value of absorbed dose can be correlated with radiation detriment from stochastic effects in all parts of the specific tissue with sufficient accuracy for the purposes of radiological protection.

The averaging of absorbed doses and the summing of mean doses in different organs and tissues of the human body, is the basis for the definition of the protection quantities. This approach implies that at low doses, where only stochastic effects are present, a linear dose-effect relationship with no threshold (LNT), and hence the additivity of doses, are an acceptable basis for radiological protection applications. It is assumed that this is valid for external as well as internal exposures. This approach was first adopted by ICRP in Publication 9 and was subsequently reaffirmed in later recommendations including Publication 60 (ICRP, 1991). The assumption of LNT in the low-dose region is based on radiobiological results with animals and epidemiological results on humans usually at higher doses as well as employing additional information from cellular and molecular radiation biology and cancer models (UNSCEAR 2000, FD-C-1). The definitions of all the protection quantities rely on this fundamental assumption.

Protection quantities are based on the averaging of absorbed dose over the volume of a specified organ (e.g. liver) or tissue (e.g. connective tissure) or region of a tissue (e.g. bone surfaces). The extent to which the mean absorbed dose is representative of the absorbed dose in all regions of the organ or tissue or tissue region depends on a number of factors. For external radiation exposure, this depends mainly on the penetrability or range of the radiation incident on the body. For penetrating radiation (photons, neutrons) the absorbed dose distribution within most specified organs may be sufficiently homogeneous and thus the mean absorbed dose is a meaningful measure of the dose throughout the organ or tissue. For radiation with low penetration or limited range (low-energy photons, charged particles) as well as for widely distributed tissues and organs (e.g. red bone marrow or lymphatic nodes) in non-homogeneous radiation fields the absorbed dose distribution within the specified organ or tissue may be very heterogeneous.

For radiations emitted by radionuclides residing within the organ or tissue, so-called internal emitters, the absorbed dose distribution in the organ depends on the penetration and range of the radiations and the homogeneity of the activity distribution within the organ or tissue. The absorbed dose distribution for radionuclides emitting alpha-particles, soft beta-particles, low-energy photons, or Auger electrons within a tissue is also likely to be highly heterogeneous.

This heterogeneity is especially significant if radionuclides emitting weakly penetrating radiation are deposited in particular parts of organs or tissues, e.g. plutonium on bone surfaces or radon daughters in bronchial mucosa and epithelia. In such situations the mean absorbed dose averaged over the entire organ or tissue may likely not be an appropriate dose quantity for estimating the expected stochastic damage. The applicability of the concept of an average organ dose and the effective dose needs, therefore, to be critically examined in such cases and sometimes empirical and more specific procedures must be applied. ICRP has addressed this issue for a number of tissues. It has developed dosimetric models for the respiratory system (ICRP 1994), the alimentary tract (ICRP in press) and the skeleton (ICRP 1979) that take account of the distribution of radionuclides and the location of sensitive cells in the calculation of mean absorbed dose to these tissues. In these cases the dose determined in target cells or subcellular targets (like cell nuclei or DNA) responsible for the development of radiation-induced cancer is treated as the average dose in an organ or tissue for the purposes of radiological protection.

As has been discussed above the heterogeneous distribution of energy deposition is of concern with respect to the averaging procedure in the low dose range and especially with radionuclides which are heterogeneously distributed in an organism and tissues and which emit particles with short ranges. However, no alternative approaches are presently available which take into account microdosimetric considerations of the three-dimensional track structure in tissues and the related energy deposition for the practice of radiological protection purposes. Considering the stochastic nature of the induction of cancer and of hereditary effects and the assumptions that one single track of ionising particles may be sufficient for the initiation process it appears questionable whether another approach is more realistic than the present use of the mean absorbed dose with the averaging procedure. Thus it is a pragmatic approach for radiological protection with a justified scientific basis. The uncertainty, however, associated with such an approach should be kept in mind.

For the case of deposition of "hot particles" in the lung, i.e. aerosols with low solubility and high specific activity, the Commission continues to consider that the associated hazard of malignant disease induction is similar to or lower than that from homogenous distribution of equal activity in the lungs (Lafuma et al. 1974, ICRP 1980; Charles et al. 2003). Irradiation of tissue to high doses from α-particles may also lead to necrosis with a large amount of cell death which in fact can decrease the risk of stochastic health effects although there may be serious damage to the function of tissues with the consequence of life threatening.

Extreme cases of inhomogeneity in dose distribution can result from the deposition of tritium or ^{125}I labelled DNA precursors (thymidine, deoxycytidine) after incorporation into DNA in cell nuclei. Due to the specific location of the emitter and very short range of tritium beta radiation and ^{125}I Auger electrons, cell nuclei can be exposed to doses which are much higher than the mean dose in the cell and of that to the organ or tissue. Therefore tritiated DNA precursors may be more radiotoxic than tritiated compounds, such as tritiated water, which are not specifically located in the cell nucleus (Streffer et al. 1977). Whereas aggregates of the proliferating cells' nuclei should be considered in such a case

of internal exposure as a subcellular target and appropriate mean dose in nuclei as the average organ or tissue dose, a concept taking these dose heterogeneities into account still has to be developed. Another approach to quantification of the health effects of predominantly intranuclear exposure and its application for radiological protection purposes, is directly based on comparisons of relevant biological effects in mammals with those of external or homogeneous internal exposure as from tritiated water.

3.3 Radiation Weighted Dose and Effective Dose

The protection quantities are used to specify dose values for limiting the occurrence of stochastic health effects below acceptable levels and avoiding tissue reactions in workers who are occupationally exposed and members of the public. The definition of the protection quantities is based on the mean absorbed dose, $D_{T,R}$, due to radiation of type R and averaged over the volume of a specified organ or tissue T. The protection quantity *radiation-weighted dose in an organ or tissue (*previously termed *equivalent dose)*, H_T,[1] is then defined by

$$H_T = \sum_R w_R D_{T,R} \tag{3.4}$$

where $D_{T,R}$ is the mean absorbed dose in a tissue T due to radiation of type R and w_R the corresponding radiation weighting factor (see Sect. 4.1, Table 4). The sum is performed over all types of radiations involved. The unit of radiation weighted dose is J kg^{-1} and has the special name sievert (Sv).

Values of w_R are mainly based upon experimental values of the relative biological effectiveness (RBE) for various types of radiations compared to the effects of x- and γ-rays at low doses (see Sect. 4.1). A set of w_R values for various radiations was given in ICRP 60 (1991). The general concept of these radiation weighting factors remains unchanged. Some modifications to the values of w_R given in the new Recommendations are given and discussed in Section 4.1.

The effective dose, E, is defined as given in Publication 60 (ICRP 1991) by

$$E = \sum_T w_T \sum_R w_R D_{T,R} \tag{3.5}$$

where w_T is the tissue weighting factor (see Sect. 4.2, Table 2) with $\Sigma\, w_T = 1$. The sum is performed over all organs and tissues of the human body considered in the definition of E. The unit of effective dose is J kg^{-1} with the special name sievert (Sv).

In spite of the limitations associated with the mean absorbed dose quantities as mentioned above, the radiation weighted dose and the effective dose further play a central role in radiological protection (see also Section 5.3).

[1]The new name *radiation weighted dose* which replaces the former name *equivalent dose* for H_T is proposed by the Commission in order to more clearly point to its definition and to avoid any further confusion with the term *dose equivalent* used in Publication 60 (ICRP 1991) for the definition of operational dose quantities.

In order to provide a practicable approach for the assessment of effective dose, in particular for occupational exposure to low doses, the effective dose and conversion coefficients are calculated for standard conditions (mono-energetic radiations, standard irradiation geometries, selected chemical compounds), relating it to the physical quantities particle fluence or air kerma in anthropomorphic phantoms with clearly defined geometries representing adult humans in the context of occupational exposure.. These phantoms include most organs and tissues in the body.

In all ICRP publications since 1979 the calculation of effective dose (before 1990 effective dose equivalent) from external radiation and radionuclides incorporated into the body was based on the radiation-weighted dose derived from gender-invariant anatomical and biokinetic models weighted by the gender-average tissue weighting factors (ICRP 1994b).

For external exposure, ICRP Publication 74 (ICRP 1996) departed from this approach and used gender-specific anatomical models and the following formula for the effective dose using gender-specific organ and tissue equivalent dose values:

$$E = w_{\text{breast}} H_{\text{breast,female}} + \sum_{\text{T}\neq\text{breast}} w_{\text{T}} \left[\frac{H_{\text{T,male}} + H_{\text{T,female}}}{2} \right] \quad . \tag{3.6}$$

In spite of applying different procedures in this ”averaging“ process, the calculations yield values of effective dose which are sufficiently precise for applications in radiological protection. The summation term includes the dose to the gonadal tissues (ovaries in the female, testes in the male).

The calculation of organ doses or conversion coefficients in case of external exposures and dose coefficients in case of internal exposures is not based on data from individual persons but on the reference values for the human body published in recent years (ICRP, 2002). In addition age-specific data may need to be considered for assessment of exposures for members of the public. The use of reference values and the averaging over both sexes indicates that the quantity effective dose is not aimed at providing an individual dose value for a specific individual human body but for a reference person or group. (More details are given in Section 5.4.)

3.4 Operational Quantities

3.4.1 Internal and External Exposure

The body related dose quantities (radiation-weighted and effective dose) are not directly measurable and, therefore, cannot be used directly in radiation protection monitoring. For that reason operational quantities have always been applied for the assessment of effective dose or mean doses in tissues or organs. Operational quantities are aimed at providing a conservative estimate or upper limit for the value of the protection quantities related to an exposure, or potential exposure of persons under most irradiation conditions. They are often

used in practical regulations or guidance instead of the protection quantities. These quantities complement the system of quantities generally applied in radiological protection. As shown in Fig. 1, different types of quantities are used for internal and external exposure situations.

For internal exposure, organ doses or effective dose are mostly assessed from the information on intake or excretion of radioactive substances . The intake is specified using the quantities specific activity or activity concentration of radionuclides in the material considered (air, food, etc.) and the amount of the material incorporated. In addition, computational models are necessary to describe the biokinetics of radioactive material in the human body and its excretion and to calculate organ and tissue doses. Model based dose coefficients have been given by ICRP for a large number of radionuclides relating the intake of a specific radionuclide to the corresponding organ and effective dose committed within a specified period (see Chapter 5) (ICRP 1994b; 1995a; 1995b; 1996a). Assessments of effective dose can also be made from measurements of the excretion of radionuclides in urine or faeces or from direct measurements using whole body monitors, using biokinetic models to interpret such data.

For radiation monitoring in cases of external exposure (area or individual monitoring) operational dose equivalent quantities are defined. Operational quantities are used for monitoring external exposures because

- protection quantities are not directly measurable,
- for area monitoring point quantities are needed, effective dose is not appropriate in area monitoring, because in a non-isotropic radiation field its value depends on the orientation of the human body in that field, and
- instruments for radiation monitoring need to be calibrated in terms of a measurable quantity for which calibration standards exist.

3.4.2 Operational dose equivalent quantities

The basic concept of the operational dose quantities for external exposure is described in the ICRU Reports 39 and 43 (ICRU 1985, 1988). The present definitions are given in ICRU Report 51 (ICRU 1993b) and more recently in ICRU Report 66 (ICRU 2001).

The quantity dose equivalent, H, is defined by

$$H = Q \cdot D \tag{3.7}$$

where D is the absorbed dose at the point of interest in tissues and Q the corresponding quality factor at this point the value of which is determined by the type and energy of charged particles passing a small volume element at this point. It is well known that the biological effectiveness of a radiation is correlated with the ionisation density along the track of charged particles in tissue. Therefore, Q is defined as a function of the unrestricted linear energy transfer, L_∞ (often denoted as LET), of charged particles in water. The quality factor function $Q(L)$ was given in ICRP Publication 60 (ICRP 1991):

$$Q(L) = \begin{cases} 1 & \text{for} \quad L < 10 \text{ keV}/\mu\text{m} \\ 0.32\,L - 2.2 & \text{for} \quad 10 \le L \le 100 \text{ keV}/\mu\text{m} \\ 300/\sqrt{L} & \text{for} \quad L > 100 \text{ keV}/\mu\text{m} \end{cases} \tag{3.8}$$

The function is the outcome of judgements taking account of results of radiobiological investigations on cellular and molecular systems as well as on results of animal experiments. The radiobiological data base for the assessment of this function is largely unchanged since 1990 (see ICRP 2003a) and changes are also not proposed now.

The quality factor Q at a point in tissue is then given by:

$$Q = \frac{1}{D} \int_{L=0}^{\infty} Q(L) D_L \, \mathrm{d}L \qquad (3.9)$$

where D_L is the distribution of D in L for the charged particles contributing to absorbed dose at the point of interest. This function is particularly important for neutrons because various types of secondary charged particles are produced in tissue in this case.

Due to the different tasks in radiological protection, including area monitoring for controlling the radiation in work places and for defining controlled or restricted areas and individual monitoring for the control and limitation of individual exposures, different operational dose quantities have been defined. While measurements with an area monitor are mostly performed free in air, personal dosemeters are usually worn at the body. As a consequence, in a given situation, the radiation field "seen" by an area monitor free in air differs from that "seen" by an personal dosemeter worn on a body where the radiation field is strongly influenced by the backscatter and absorption of radiation in the body. The use of different operational dose quantities allows for such phenomena.

For the different tasks of monitoring of external exposure the following quantities are defined:

Task	Operational quantities for	
	area monitoring	individual monitoring
Control of effective dose	ambient dose equivalent $H^*(10)$	personal dose equivalent $H_p(10)$
Control of skin dose	directional dose equivalent $H'(0.07, \Omega)$	personal dose equivalent $H_p(0.07)$

With respect to the application of the operational quantities the ICRU (1993) has stated that $H^*(10)$ and $H_p(10)$ are designed for monitoring strongly penetrating radiation, e. g. photons (above about 12 keV) and neutrons, while $H'(0.07,\Omega)$ and $H_p(0.07)$ are applied for monitoring weakly penetrating radiation, e. g. α- and β-particles. Further-more, $H_p(0.07)$ is also used for monitoring the doses to the extremities from all ionising radiation.

For the special case of controlling the dose to the lens of the eye the directional dose equivalent, $H'(3,\Omega)$, and personal dose equivalent $H_p(3)$ have been defined. These quantities, however, have never been used in practice and no instruments exist for measuring these quantities. It is suggested that their use is discontinued because the monitoring of the exposure to the eye lens is also

sufficiently achieved if the dose to the eye lens is assessed in terms of the other operational quantities. While for photon exposure $H_p(10)$ is always sufficient, for charged particle exposure (β-particles, α-particles) mainly $H_p(0.07)$ should normally be used for this purpose (ICRU 1998).

An operational quantity for individual monitoring should allow the effective dose to be assessed or should provide a conservative estimate under nearly all irradiation conditions. This, however, requires that the personal dosemeter must be worn at a position on the body which is representative with respect to the exposure. For a dosemeter position in front of the trunk the quantity $H_p(10)$ mostly furnishes a conservative estimate of E even in cases of lateral or isotropic radiation incidence on the body. In cases of exposure from the back only, however, a dosemeter worn at the front side and correctly measuring $H_p(10)$, will not appropriately assess E. Also in cases of partial body exposures the reading of a personal dosemeter may not provide a representative value for the assessment of effective dose.

While in most practical situations of external radiation exposure the operational dose quantities fulfil the aim to provide a conservative estimate or upper limit for the value of the limiting quantities, this is not always the case in high energy radiation fields as given near high energy accelerators or in space (Pellicioni 1998). The location at which secondary charged particle equilibrium is achieved is very important in these cases and a depth of 10 mm in ICRU tissue, as defined with the operational quantities, is not sufficient if the charged particle built-up is only performed in the 10 mm thick ICRU material in front of that point. This problem needs further consideration. In radiation fields relevant for aircrew exposure, however, H*(10) appears to be appropriate if the proposed radiation weighting factors for protons and neutrons (see Sections 4.1.3 and 4.1.4) are considered.

3.4.3 Operational quantities for area monitoring

3.4.3.1 ICRU sphere phantom

For all types of radiation the operational quantities for area monitoring are defined on the basis of a dose equivalent value at a point in a simple phantom, the ICRU sphere. It is a sphere of tissue-equivalent material (30 cm in diameter, density: 1 g cm^{-3}, mass composition: 76.2 % oxygen, 11.1 % carbon, 10.1 % hydrogen and 2.6 % nitrogen). For radiation monitoring it adequately approximates the human body as regards the scattering and attenuation of the radiation fields under consideration.

3.4.3.2 Aligned and expanded radiation field

The operational quantities for area monitoring defined in the ICRU sphere should retain their character of a point quantity and the property of additivity. This is achieved by introducing the terms "expanded" and "aligned" radiation field in the definition of these quantities.

An *expanded* radiation field defined as a hypothetical field is a radiation field in which the spectral and the angular fluence have the same values in all points of a sufficiently large volume equal to the values in the actual field at the point of

interest. The expansion of the radiation field ensures that the whole ICRU sphere is thought to be exposed to a homogeneous radiation field with the same fluence, energy distribution and directional distribution as in the point of interest of the real radiation field.

If all radiation is (thought to be) *aligned* in the *expanded* radiation field so that it is opposed to a radius vector Ω specified for the ICRU sphere, the aligned and expanded radiation field is obtained. In this fictitious radiation field, the ICRU sphere is homogeneously irradiated from one direction, and the fluence of the field is the integral of the angular differential fluence at the point of interest in the real radiation field over all directions. In the expanded and aligned radiation field, the value of the dose equivalent at any point in the ICRU sphere is independent of the directional distribution of the radiation of the real radiation field.

3.4.3.3 Ambient dose equivalent, *H**(10)

For area monitoring the operational quantity for strongly penetrating radiation is the ambient dose equivalent, $H^*(10)$, defined by:

> The *ambient dose equivalent*, $H^*(10)$, at a point of interest in the real radiation field, is the dose equivalent that would be produced by the corresponding aligned and expanded radiation field, in the ICRU sphere at a depth of 10 mm, on the radius vector opposing the direction of radiation incidence.

Different to former definitions, the quantity *ambient dose equivalent* is now restricted to be defined for a given depth of 10 mm and, therefore, strongly penetrating radiation only (ICRU 2001). In practice, however, this has always been realised because for this quantity other depths than 10 mm in the sphere have never been used.

3.4.3.4 Directional dose equivalent, *H'(d,Ω)*

For area monitoring of weakly penetrating radiation the operational quantity is the directional dose equivalent, $H'(0.07,\Omega)$ or, in rare cases, $H'(3,\Omega)$ defined by:

> The *directional dose equivalent*, $H'(d,\Omega)$, at a point of interest in the actual radiation field, is the dose equivalent that would be produced by the corresponding expanded radiation field, in the ICRU sphere at a depth d, on a radius in a specified direction Ω.
>
> For weakly penetrating radiation it is d = 0.07 mm and $H'(d,\Omega)$ is then written $H'(0.07,\Omega)$.
> In case of monitoring the dose to the lens of the eye $H'(3,\Omega)$ with d = 3 mm was recommended for use by the ICRU. As mentioned above, it is proposed, that $H'(3,\Omega)$ should not be used for monitoring.

In practice, $H'(0.07,\Omega)$ is almost exclusively used in area monitoring for low-penetrating radiation. For unidirectional radiation incidence the quantity may be written $H'(0.07,\alpha)$, where α is the angle between the direction Ω and the direction opposite to radiation incidence. In radiological protection practice the

direction Ω is often not specified, because it is mostly the maximum value of $H'(0.07,\Omega)$ at the point of interest which is of importance. It is usually obtained by rotating the dose rate meter during the measurement and looking for the maximum reading.

3.4.4 Operational quantities for individual monitoring

Individual monitoring of external exposure is usually performed with personal dosemeters worn on the body and the operational quantity defined for this application takes into account this situation. The true value of the operational quantity is determined by the irradiation situation near the point where the dosemeter is worn. For individual monitoring the operational quantity is the personal dose equivalent, $H_p(d)$.

> The *personal dose equivalent*, $H_p(d)$, is the dose equivalent in ICRU tissue at a depth d in a human body below the position where an individual dosemeter is worn.

For penetrating radiation a depth d = 10 mm and for weakly penetrating radiation a depth d = 0.07 mm is recommended.

In special cases of monitoring the dose to the lens of the eye a depth d = 3 mm has been proposed to be appropriate. In practice, however, $H_p(3)$ has never been used, no dosimeters are available and its use, therefore, is no longer recommended.

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4 Weighting Factors

The Commission has recognised that absorbed dose is insufficient, on its own, for assessing harm caused by radiation exposure. Some radiations are more likely to induce stochastic effects than x- and γ-rays at low doses and stochastic effects are more likely in some tissues than in others. As noted previously, in order to establish a correlation between dose quantities applied in radiological protection and the effects considered two types of weighting factors have been introduced, a radiation weighting factor, w_R, and a tissue weighting factor, w_T.

The weighting factors are intended to take account empirically of many types of radiation and of stochastic effects (radiation-induced cancer and hereditary diseases) in different organs and tissues of the body. They are therefore broadly based on a wide range of experimental data and epidemiological studies. In ICRP Publication 60 (ICRP, 1991) the Commission selected a general set of these weighting factors that were considered to be sufficiently accurate and appropriate for the needs in radiological protection (Tables 1 and 3).

The procedure of summing of weighted doses, like that of averaging of doses, is appropriate for radiological protection only if the dose-effect relationship shows an increase in risk proportionate to the dose (see Section 3.2.) The weighting factors and the dosimetric quantities based on w_R and w_T relate only to stochastic health effects.

4.1 Radiation Weighting Factors

The method of radiation weighting in the definition of radiological protection quantities has been used since the early 1960s. Before 1991 this was achieved by generally applying the quality factor concept using a specified $Q(L)$ function (ICRP 1987). In Publication 60 (ICRP 1991) the radiation weighting was defined differently for the protection quantities and the operational dose quantities used in measurements of external exposure.

The radiation weighting is based mainly on the evaluation of the relative biological effectiveness (RBE) of the different radiations with respect to stochastic effects. The RBE is used in radiobiology for characterising the different biological effectiveness of radiations. RBE values are given as the ratio of the absorbed doses of two types of radiation producing the same specified biological effect in identical irradiation conditions (dose value of a reference radiation divided by the corresponding dose value of the radiation considered). RBE values for a certain radiation depend upon the conditions of exposure including the biological effect investigated, the tissue or cell type involved, the dose and the dose rate, and the dose fractionation scheme; therefore for a given type and energy of radiation there is a range of RBE values. For radiological protection the RBEs at low doses and low dose rates are at a maximum (RBE_M) and therefore RBE_M is of particular interest for defining radiation weighting factors. The weighting factors are defined to be independent of the dose and dose rate in this dose region.

The concept of the quality factor is based on the differences in the biological effectiveness of the different types of radiation which have their origin in the differences of their energy deposition properties along the tracks of charged particles. For applications in radiological protection the complex structure of the charged particle tracks in tissue are characterised by a single parameter only, the unrestricted linear energy transfer, L_∞, (often denoted linear energy transfer, *LET* or L) and the quality factor Q is defined by a function of L as given in various publications ICRP and ICRU (ICRP 1963, 1977, 1991, ICRU 1970, 1986).

A feature of the energy transfer of low- and high-LET particles is also the difference in the event distribution as has already been mentioned in Section 3.1. This effect influences the biological effectiveness at low doses.

For the protection quantities the radiation weighting factor, w_R, has been defined. It is a factor by which the mean absorbed dose in any tissue or organ is multiplied to account for the detriment caused by the different types of radiation relative to photon radiation. Numerical values of w_R are specified in terms of type and energy of radiations either incident on the human body or emitted by radionuclides residing within the body. Values of w_R adopted in Publication 60 are given in Table 3.

The same value of the radiation weighting factor, w_R, is applied to all tissues and organs independent of the fact that the actual radiation field in the body may vary between different tissues and organs due to attenuation and degradation of the primary radiation and the production of secondary radiations of different radiation quality in the body. The value of w_R may, therefore, be seen as a factor

representing radiation quality averaged over the different tissues and organs of the body.

The averaging procedure implied in the w_R has raised some concern especially in the case of external low energy neutron radiation exposure where secondary photons (low-LET radiation) contribute significantly to tissue and organ doses (Dietze, 1994). Therefore the mean radiation quality in a tissue or organ exposed to low-energy neutrons depends on its position in the body and varies with the direction of neutron incidence to the body.

In Publication 92 (ICRP, 2003a) this problem of bi-locality of specifying radiation quality and absorbed dose is discussed in detail. A proposal is made how to achieve an improved radiation weighting factor for neutrons. In that report a modified function for the radiation weighting factor for neutrons is presented and a fixed relationship is proposed between the radiation weighting factor and a mean quality factor averaged over the human body and calculated for isotropic exposure. This report does not, however, fully support this procedure. Details are given in Section 4.1.3.

Ideally the decision on w_R values would be predominantly based on RBE data from *in vivo* investigations with animals related to stochastic effects. Often cancer and leukaemia induction or life-time shortening after whole-body exposure have been studied. While *in vitro* investigations with cells can provide important contributions to the understanding of basic mechanisms regarding carcinogenesis, the RBE values obtained in such studies are likely to be less well correlated with carcinogenesis in humans. In many cases, however, there are not enough or not sufficiently precise data available from *in vivo* investigations on animals on the range of radiation qualities of interest in radiological protection.. Therefore the $Q(L)$ function which is mainly based on data from in vitro experiments (NCRP 1990) is applied for the calculation of a mean Q-value for the human body which in turn is then used for estimating radiation weighting factor values. This is especially the case for protons and heavy ions, and to a large extent for neutrons (ICRP 2003a).

Generally, a broad range of RBE values have been obtained in investigations of various biological effects which do not exhibit a direct relationship to the effects for which radiation weighting factors are required. Experimental RBE values are often associated with large uncertainties due to the small numbers of animals used and many other influencing factors. For these reasons, the weighting factors are carefully selected to give a representative value for the known data and to be sufficiently accurate for the application in radiological protection. As soon as the values of Q and w_R are selected and fixed by convention, as part of a quantity, they are as such not associated with an uncertainty (see Chapter 6).

4.1.1 Reference Radiation

Values of RBE depend on the reference radiation chosen. Generally low-LET radiation is taken as a reference and mostly ^{60}Co-gamma rays or medium to high energy x-rays have been used in experimental investigations of RBE. There exists, however, no international agreement on selecting photons of a specific type or energy as a general reference radiation. Therefore, for all RBE data published information on the reference radiation used is necessary.

In Publication 60 (ICRP 1991) the ICRP recommended a radiation weighting factor value w_R=1 for all photons (Table 3). This is consistent with the fact that no specific photon energy has been fixed as a reference and therefore an average of RBE data related to photons of different energies is applied. It does not, however, imply that no differences exist in radiation quality for photons of different energy.

One argument for this approach is the generation of secondary radiation in the human body. If a body is exposed to mono-energetic gamma radiation, the resulting photon radiation field inside the body comprises not only the incident radiation, but also a large fraction of scattered photons with much lower energies resulting from single and multiple Compton scattering (Harder 2004). This situation is quite different from that in investigations on small micro-organisms or single cells, where the scattered photon contribution to the total dose is negligible. It is, therefore, justified for the selection of radiation weighting factors with respect to the human body to use an average of experimental RBE data related to radiation fields which use as a reference, either high energy (> 200 keV) x-rays or ^{60}Co-gamma radiation.

As a consequence ICRP has used a broad range of RBE_M values related to different photon fields (mostly ^{60}Co γ-rays or high energy x-rays) for the evaluation of w_R values for other radiations. Although this approach has resulted in some debate it has allowed most of the available experimental RBE data to be taken into account in the selection of w_R values.

4.1.2 Radiation weighting factor for photons, electrons and muons

Photons, electrons and muons are low-LET radiations with LET-values of less than 10 keV/µm. Low-LET radiations have always been given a value of one in radiation weighting. Before 1991 this has been achieved by setting $Q(L) = 1$ for $L < 3.5$ keV/µm. ICRP Publication 60 (1991) continued this practice by defining $w_R = 1$ for these radiations and for operational quantities also $Q(L) = 1$ for $L < 10$ keV/µm (see eq.3.8). This has been done mainly for practical reasons and in part in consideration of the large uncertainties in estimating radiation risk factors which did not justify a more detailed description.

In ICRP Publication 92 (ICRP 2003a) details on RBE values for low-LET radiation are presented and the consequences with respect to the weighting of different photon radiations are discussed. Other recent publications also deal with this subject (e.g. SSK 2004, Harder 2004).

In vitro investigations of dicentrics in human lymphocytes, (e. g. by Sasaki 1991; Schmid 2002; Guerrero-Carbajal 2003) and for mutations and transformations in other cell lines, e. g. in human and human-hamster hybrid cells by Frankenberg et al. (2002), have shown that low energy x-rays have a significantly larger RBE than ^{60}Co-gamma rays. Thus, 20 keV x-rays may be about 2 to 3 times as effective as conventional 200 kV x-rays and these are about twice as effective as ^{60}Co-gamma rays. A much lower ratio has been observed in animal experiments while epidemiological data are not precise enough to see any differences.

While photons of 1 to 5 MeV are obviously less effective than x-rays, the situation may be different for very high energy photons e. g. near high energy accelerators or in radiation fields of cosmic rays. Such photons are able to produce secondary particles, e. g. neutrons or other high-LET particles. It is, therefore, assumed that the RBE of these photons is higher than that of photons of about 1 to 5 MeV.

In Publication 60 the ICRP has stated that "simplicity is important to reflect our lack of precise information in man and an appreciation of the practical aspects of radiological protection. For example, the Commission does not believe it is helpful to adopt different quality-factor values for different photon energies". There are now more data available from investigations on cells showing significant differences in radiation quality of photons of different energies. However, there are practical arguments for keeping a single w_R value for all photons and electrons (Dietze 2004).

As has already been pointed out in the case of external exposure to photons with energies from 30 keV to 5 MeV a considerable part of the organ doses are from Compton-scattered photons in the body with an average energy significantly lower than that of the incident photons (Harder 2004). In deep-lying organs this portion can amount to about 50 % of the total organ dose for 1 MeV photons. Therefore, for external photon radiations with different energies the variation of the mean RBE averaged over the whole body is considerably smaller than the corresponding differences obtained from investigations of thin cell layers in vitro (frequently mono-layers).

Furthermore, the external low-energy photon radiation (less than about 30 keV) which is assumed to have an RBE much higher than 1, is already strongly attenuated in tissue close to the surface of the body and can be easily shielded. Hence, its contribution to the effective dose is mostly small. This may not be the case in low-energy x-ray fields as used in mammography where no high-energy photons are present. Here the following argument should be considered.

In radiation protection measurements the operational dose quantities $H^*(10)$ and $H_p(10)$ are used to assess effective dose. For photons with energies between 10 keV and 40 keV, the values of $H^*(10)$ and $H_p(10)$ provide a very conservative estimate of E, up to a factor 6 higher for frontal irradiation (AP) and for $H^*(10)$ and even more for other directions of radiation incidence (PA, LAT, ROT, ISO) (ICRP 1996b).

In internal dosimetry, a single w_R-value for all photons and electrons emitted is a major simplification in the determination of radiation-weighted organ doses. The above practical arguments for keeping a single w_R vaue for photons and electrons are equally applicable to the dosimetry of photon and electron emitters distributed in the body. Considering these arguments, it can be expected, with exception of a few cases such as tritium incorporated into the DNA, that the single-value of w_R for photons and electrons provides sufficient precision for the purposes of radiation protection

These facts are good arguments for continuing to use a w_R of 1 for all low-LET radiations. It is, however, important to state that this simplification is sufficient only for the intended application of effective dose, e.g. for dose limitation,

assessment and controlling of doses. It is not intended for retrospective assessment of individual risks of stochastic effects from radiation exposure. In cases of individual retrospective dose assessment more detailed information on the radiation field and appropriate RBE values should be considered if available (see Section 5.4).

4.1.3 Radiation weighting factors for neutrons

The radiation weighting factor for neutrons mainly reflects the relative biological effectiveness of neutrons following external exposure. Radionuclides emitting neutrons are infrequent and their contribution to effective dose is generally low.

The radiation quality of neutrons incident on the human body is strongly dependent on the neutron energy because of the variation of the secondary radiation with energy. Qualitatively, the folloewing effects are important: the production of secondary photons by neutron absorption in tissue at low neutron energies , the increase of the energy of recoil protons with increasing neutron energy, the release of heavier charged particles at higher energies and nuclear spallation processes at very high energies..

In Publication 60 (ICRP 1991) the radiation weighting factor for neutrons has been given in two ways, by a step function defining 5 neutron energy ranges with w_R values of 5, 10 and 20, respectively (Table 3) and by a continuous function for use in calculations. The tabulated values of w_R have not been generally accepted as useful and in practice, the continuous function has frequently been applied. This is due to the fact that most neutron fields contain neutrons with a broad energy spectrum and very often calculations using energy dependent conversion coefficients are performed for estimating doses. All internationally recommended conversion coefficients, including those given in Publication 74 (1996) are based on the continuous function. It is, therefore, recommended that in future only a continuous function is given for defining radiation weighting factors for neutrons. It should be noted, however, that the use of a continuous function is based on practical considerations only and does not imply the availability of more precise data.

In Publication 60 (1991) a maximum w_R value of 20 has been fixed. In Publication 92 (ICRP 2003a) it is stated that in the energy region near 1 MeV the maximum value of w_R for neutrons of about 20 is still an acceptable approximation. This judgement is not based on a specific experimental value but rather reflects a representative value considering the broad range of RBE values from experimental animal data obtained from investigations using fission neutrons from reactors (ICRP 2003a). It is, therefore, proposed to retain this value for neutron energies at about 1 MeV.

The production of secondary photons in the human body if exposed to neutron energies below 1 MeV, is mainly responsible for the decrease of the neutron weighting with decreasing energy. In this energy range this effect is much larger than the influence of the change in the LET-distribution of the neutron-produced secondary charged particles, mainly protons. When RBE-data for low-energy neutrons obtained from investigations with small animals are used as the basis for the evaluation of w_R-values for human exposure it has to be taken into

account that in the human body the dose contribution from secondary photons is higher than in the smaller species used in the experiments like mice (Dietze 1994). These photons are mainly produced by the capture of degraded neutrons and their contribution to the total radiation weighted dose of an organ is strongly dependent on the body size and on the position of the organ in the body. For external neutrons and whole body exposure a mean value can be determined as an average over all tissues and organs of the human body considering, however, the tissue weighting factors in the averaging procedure. At the time of Publication 60 (ICRP 1991) data from calculations with neutrons in anthropomorphic phantoms were not available and the ICRU sphere was taken as a surrogate. It has been shown (ICRP 2003a, SSK 2004) that for neutrons below about 1 MeV, the full consideration of the secondary photons result in considerably lower values for mean quality factors and thus of w_R than those given in Publication 60 (ICRP 1991).

In Publication 92 (ICRP 2003a) one suggestion is that the energy dependence of the radiation weighting should be based on the $Q(L)$ function defined in ICRP Publication 60 and the calculation of a human body averaged mean quality factor q_E (see eq. (4.2)) and then the relationship between q_E and a weighting factor is fixed by a function

$$w_R = 1.6\ (q_E - 1) + 1 \qquad (4.1)$$

This equation preserves a value of w_R of about 20 at neutron energies near 1 MeV. Calculations of q_E have been performed considering the dose distribution in the human body and the tissue weighting factors w_T of the different organs and tissues by the equation

$$q_E = \sum_T w_T Q_T D_T \Big/ \sum_T w_T D_T \ , \qquad (4.2)$$

where Q_T is the mean quality factor in the tissue or organ T and D_T the corresponding mean absorbed dose. Due to the different w_T-values of the organs and tissues not symmetrically distributed in the human body the value of q_E depends on the directional incidence of the radiation on the body. Calculations have shown that for thermal neutrons the deduced w_R (eq. 4.1) may vary from 2.5 (for ISO and ROT incidence) to 3.2 (for AP incidence) for the various exposure conditions and that there are also differences depending on the gender of the selected model. In general, the value of q_E depends also on the model of the human body, e. g. if the calculations are performed with a MIRD-type phantom or a voxel type phantom (see Sect. 5.3).

In principle, the idea of defining a general relationship between w_R and a mean quality factor q_E for all types and energies of particles as given in eq. (4.1) is attractive because it more clearly points to the common basis of the concept of radiation weighting and quality factor used in the definition of the operational quantities, the data set of RBE values available. In practice, however, eq. (4.1) can only be applied to strongly penetrating external radiation, e. g. neutrons, protons and heavy ions. In addition, a factor of 1.6 has been introduced in eq. (4.1) in order to fit the calculated w_R-value for 1 MeV neutrons to experimental data. It is questioned, whether it is justified to extend this factor to other particles and energies with different secondary charged particle spectra. Another disadvantage of defining this strong relationship may be the fact that q_E depends

on many parameters, such as. the phantom selected, the w_T-values, the exposure situation chosen and even the computer code used. Many parameters may give rise to changes in future while w_R should remain stable. Equation 4.1 is therefore used as a guide in establishing values of w_R.

For neutron energies of less than 1 MeV a similar energy dependence of the radiation weighting for neutrons has been obtained also by other considerations (SSK 2004, Dietze 2004) without using a fixed relationship between Q and w_R.

It is based on the assumption that in the low-energy range the effect due to secondary photons mainly determines the energy dependence of the neutron weighting for the human body and that for a small tissue probe the mean RBE value for the neutron-induced high-LET component ($RBE_{high\text{-}LET}$, mainly determined by recoil protons, protons from N(n,p) and heavier ions) is approximately independent on neutron energy.

First the mean absorbed dose contribution, $f_{low\text{-}LET}$, from secondary photons (low-LET component relative to the total dose) in the human body and the contribution from secondary charged particles (high-LET component) have been calculated by:

$$f_{low\text{-}LET} = (\Sigma\, w_T\, D_T\, f_{low\text{-}LET,T}) \,/\, (\Sigma\, w_T\, D_T) \quad \text{and} \tag{4.3}$$

$$f_{high\text{-}LET} = 1 - f_{low\text{-}LET} \tag{4.4}$$

where $f_{low\text{-}LET,T}$ is the relative absorbed dose contribution in the tissue or organ T from secondary low-LET radiation. Secondly a "mixing rule" has been applied for the calculation of a body-averaged relative biological effectiveness using the equation:

$$RBE_{av} = RBE_{high\text{-}LET}\,(1 - f_{low\text{-}LET}) + RBE_{low\text{-}LET}\, f_{low\text{-}LET} \tag{4.5}$$

where RBE_{av} is the resulting RBE properly averaged over the human body. This "mixing rule" is applied in the neutron energy range from thermal up to 1 MeV. For the photon contribution a value of $RBE_{low\text{-}LET} = 1$ is taken and for the high-LET component a value of $RBE_{high\text{-}LET} = 25$ is chosen which is consistent with experimental data of the induction of dicentrics in tissue cells (Schmid et al. 2004). The selected RBE-values result in an RBE_{av} value of about 20 in the human body for neutrons of 1 MeV which is consistent with the value mentioned above. Depending on the exposure conditions chosen, the energy dependence of RBE_{av} is similar to that of w_R calculated by eq. (4.1) in the energy range from thermal up to 1 MeV neutrons.

In view of all these considerations a continuous function is recommended for the definition of the radiation weighting factor in the energy range below 1 MeV:

$$w_R = 2.5 + 18.2 \exp[-(\ln E_n)^2/6] \qquad \text{for} \qquad E_n < 1 \text{ MeV} \tag{4.6}$$

Figure 2 shows that in the neutron energy range below 1 MeV the values of w_R are much less than those given in ICRP Publication 60 (1991). The judgement

now fully considers the effect of secondary photons in the body and is0 better related to the mean quality factor q_E as given in ICRP Publication 92 (2003a).

The energy range above 1 MeV needs different considerations. In this high energy range there are almost no new experimental data available from investigations of animals. All existing experimental data either on animals or on cells, however, show a strong decrease of RBE with increasing neutron energy. This is consistent with calculations based on the $Q(L)$ function (ICRP 2003a). If, however, the strong relationship between q_E and w_R as defined in ICRP Publication 92 (ICRP 2003a) were to be applied this would result, in the energy range between 5 MeV and 100 MeV, in an increase of w_R for neutrons of about 30 %relative to the data of the continuous function as defined in ICRP Publication 60. In principle, this difference is seen to be much less than the general uncertainty of RBE-values in this energy range. From a practical point of view it seems, therefore, more appropriate, not to apply minor changes to the existing function in this energy range but to stay with the values already defined in Publication 60 (ICRP 1991).

There are no experimental data forvery high neutron energies above about 50 MeV . The calculations of Pelliccioni (1998; 2004) and Yoshizawa et al. (1998), however, have shown that the mean quality factor averaged over the human body is decreasing with increasing neutron energy to values of much less than 5 and reaches values near to those of protons at very high energies above 1 GeV. While this topic may need also more detailed considerations in future, a continuous weighting factor function for neutrons with energies above 50 MeV is proposed here considering this fact. Its value is decreasing with increasing energy from about 5.5 at 50 MeV to about 2.5 at 10 GeV. This function fits with the function for lower neutron energies at 50 MeV and the energy dependence of the data from Pellicioni (1998; 2004) and Yoshizawa (1998) and the new w_R-value of 2 for protons have been used as a guideline for the higher energies.

The following continuous function is now recommended for the calculation of radiation weighting factors for neutrons:

$$w_R = \begin{cases} 2.5 + 18.2\, e^{-[\ln(E_n)]^2/6} & , \quad E_n < 1\ \text{MeV} \\ 5.0 + 17.0\, e^{-[\ln(2E_n)]^2/6} & , \quad 1\ \text{MeV} \le E_n \le 50\ \text{MeV} \\ 2.5 + 3.25\, e^{-[\ln(0.04E_n)]^2/6} & , \quad E_n < 50\ \text{MeV} \end{cases} . \qquad (4.7)$$

Obviously these functions look complex. The calculations do not reflect the precision of the biological data but are an empirical approach describing the weighting of neutrons over more than 12 decades of neutron energy.

The foregoing extensive discussion of this important matter of energy dependence of w_R for neutrons can be summarized as follows: a proposal is made for a w_R function for neutrons which is a modification of that made in ICRP Publication 92 (2003a). It is mainly based on the following chosen criteria:

- For neutrons of about 1 MeV a maximum w_R-value of about 20 is retained as proposed in ICRP 92 (2003a).
- Values for w_R for E_n < 1 MeV are similar to those proposed in ICRP 92 Publication (2003a).

- The general shape of the curve for the energy dependence of w_R is based on that related to the mean quality factor q_E.
- For physical reasons, w_R should asymptotically approach a value similar to that of protons at high energies (> 100 MeV) (for which some radiobiological data exist). Based on calculations by Pellicioni (1998; 2004) and Yoshizawa (1998) an asymptotic value of 2.5 at neutron energies above 1 GeV is used.
- Using these criteria and for practical reasons a continuous function for w_R of neutrons has been derived.

The resulting function (Figure 2) is consistent with existing relevant biological and physical knowledge. While in principle it would be desirable to use the same procedure for considering the radiation quality in the definition of protection and operational dose quantities, this has not been achieved in this proposal. For the practice in radiological protection it seems, however, to be more important that the operational dose quantities provide a conservative estimate of effective dose under most exposure conditions. This is achieved when applying the radiation weighting factors for neutrons as proposed in eq. (4.7). Furthermore, at very high neutron energies preference is given to the consistency of w_R values for neutrons and protons.

4.1.4 Radiation weighting factor for protons

Only external radiation sources have to be considered for proton exposure in practical radiological protection. In Publication 60 a radiation weighting factor of 5 was recommended for all protons with energies above 2 MeV except recoil protons (Table 3).

In recent years proton radiation has received more attention due to an increased interest in dose assessment for air crew exposure and in space. In these cases external proton radiation is cosmic radiation. In these radiation fields very high energy protons strongly dominate and protons with energy of a few MeV are not relevant, even when considering the increasing radiation quality at low energies. The range of low energy protons is also small (range of 4 MeV protons in tissue: 0.025 cm in tissue; 10 MeV protons: 0.13 cm) and they will mostly be absorbed in the skin with a tissue weighting factor, w_T, of 0.01.

For applications in radiological protection it seems to be sufficiently accurate defining only one w_R-value for protons of all energies. When choosing a value of the radiation weighting factor for protons it then would be appropriate to look for data from high energy protons which are most relevant in cosmic radiation fields.

There are very few investigations using animals that give information on the RBE for high energy protons. Mostly RBE values between 1 and 2 are observed. With respect to the ionisation density in tissue, high energy protons can be regarded as low-LET radiation (with a mean LET-value much less than 10 keV/μm) and the mean quality factor of 100 MeV protons stopping in tissue is calculated to be less than 1.2 (ICRP, 2003a). At very high proton energies near 1 GeV secondary

charged particles from nuclear reactions become more important and the mean quality factor increases up to about 1.8.

Taking all considerations and available data into account, it is proposed that the radiation weighting factor adopted for protons in the new Recommendation should be 2 rather than 5 as in Publication 60 (see Table 4).

4.1.5 Radiation weighting factor for α-particles

Humans are predominantly exposed to α-particles from internal emitters, e.g. from inhaled radon progeny or ingested α-emitting radionuclides like radium, uranium, thorium and plutonium. There are a number of epidemiological studies that provide information on the risk for inhaled or intravenously injected α-emitters. The distribution of radionuclides and the dosimetry in the body and also the estimation of dose distributions in tissues and organs are very complex and the doses calculated are highly dependent on the models used. The estimated doses are, therefore, associated with substantial uncertainties. For this reason epidemiological as well as experimental studies cannot be used as the main basis for an assessment of the RBE for α-emitters although they can provide valuable guidance. From calculations using stopping power data for α-particles in tissue and the $Q(L)$ function the mean quality factor of a 6 MeV alpha particle slowing down in tissue is estimated to be about 20.

Judgements on the available data and a selection of a w_R value for α-particles have been reviewed by (ICRP 2003a).

It was concluded in ICRP Publication 92 (para 376, 2003a) that: "Internal emitters must be treated as a separate case because their RBE depends not merely on radiation quality, but also, and particularly for α-rays with their short ranges, on their distribution within the tissues or organs. It is, accordingly, unlikely that a single w_R should adequately represent the RBE_M for different α emitters and for different organs, and this is specifically so because of the remaining uncertainties for leukaemia and other blood dyscrasias. The current w_R of 20 for α-rays can, thus serve as a guideline, while for specific situations, such as exposure to radon and its progeny, or the incorporation of ^{224}Ra, ^{226}Ra, thorium, and uranium, more meaningful weighting factors need to be derived. This can be achieved either in terms of specific assumptions on critical target cells and the resulting dosimetric models, or it is done on the basis of epidemiological information. Specifically, it follows from these considerations that a convention in terms of LET should not include the case of α rays."

As recent data do not strongly support the need for a change of the radiation weighting factor for alpha particles it is proposed that the w_R value of 20 is retained for the new recommendations (see Table 4).

4.1.6 Radiation weighting factors for heavy ions, fission fragments and other particles

Doses from fission fragments are of importance in radiological protection mainly in internal dosimetry and the situation regarding radiation weighting factors may be seen as similar to that for α-particles. Due to their short ranges the biokinetics and distribution of the actinides in the organs and tissues are very

important and have a strong influence on their biological effectiveness. A radiation weighting factor of 20 as given in Tables 3 and 4 equal to that for α-particles may therefore be seen as a rough conservative estimate. The short range of the fission fragments in tissue and the high energy transferred, therefore, to a small volume of tissue results in a very high local dose at this point which may reduce their RBE. This is mainly due to the killing of potential cancer cells by this highly localised delivery of radiation doses which results in "energy wastage". As has been discussed in Sect. 3.2 care must be taken when applying the concept of mean organ or tissue doses in such cases and specific considerations are necessary.

In external exposure heavy ions and other types of radiation, e. g. pions, which are not mentioned in the list of w_R-values (Tables 3 and 4) are mainly encountered in radiation fields near high energy accelerators, at aviation heights and in space. There are only few RBE data for heavy ions and most of these are based on *in vitro* experiments. ICRP Publication 92 (ICRP 2003) provides an overview on radiobiological data where RBE values have been derived and which are relevant for defining radiation weighting factor values.

For heavy ions the data obtained by in vitro experiments clearly show an LET dependence of RBE. The RBE decreases with increasing LET for LET values above about 150 keV/μm. For heavy charged particles incident on a human body and stopped in the body the radiation quality of the particle changes strongly along the track. An averaged value may be chosen to derive a w_R. The selection of a constant w_R value of 20 for all types and energies of heavy charged particles is seen to be a rough estimate sufficient for the general application in radiological protection. For applications in space where these particles contribute significantly to the total dose in the human body, a more realistic approach may be chosen based on the calculation of a mean quality factor in the human body as mentioned in Sect. 4.1.3. In operational circumstances health physicists should make their own judgements on values of w_R when sufficient relevant data are available.

In cases where radiation weighting factors are needed for particles other than those included in Table 4, it is proposed to follow the procedure given in eq. 4.2 in Section 4.1.3. Based on the $Q(L)$ function given in Publication 60 (ICRP 1991) a quality factor q_E averaged over the human body should be calculated (eq. (2) in 4.1.3) as has already been applied for pions (Pellicioni 1998, 2004).

4.2 Tissue Weighting Factors

The definition of effective dose also takes into account the different radiosensitivities of the various organs and tissues in the human body with respect to radiation detriment from stochastic effects. For this purpose, weighting factors, w_T, were introduced in ICRP Publication 26 for six identified tissues and for a remaining group of tissues (collectively referred to as the "remainder"). In ICRP Publication 60 tissue weighting factors were specified for twelve tissues and organs and the "remainder" (Table 1). The sum of the tissue weighting factors is unity so that a uniform dose distribution in the whole body gives an effective dose numerically equal to the radiation-weighted dose in each organ and tissue of the body.

The tissue weighting factors determined for the new recommendations are based on detriment-adjusted nominal risk coefficients (Committee 1 Foundation Document). The unadjusted nominal risk coefficients are calculated by averaging estimates of the radiation-associated lifetime risk for cancer *incidence* for two composite populations. For each of these populations, the detriment is modelled as a function of life lost, lethality and loss of quality of life. With a few exceptions the parameters in the risk models are estimated using cancer incidence data from the studies of the Japanese atomic bomb survivors. Both excess relative risk and excess absolute risk models are developed for most sites. The relative radiation detriments are similar to the values calculated in Publication 60 except for some organs: breast, gonads and remainder tissues. In addition specific w_T values are now given for the brain, kidneys and salivary glands. The tissue weighting factors proposed by ICRP for the new Recommendations are given in Table 2.

The tissue weighting factors, w_T, are applied to workers, to the whole population including children and to both genders. Recently they have also been applied to the developing fetus (Publication 88 ICRP 2001), although it was recognised that the w_T values had been developed for exposure of individuals after birth and that the apportionment of radiation detriment which the use of these values imply may not be appropriate for doses received *in utero*. The approach was, however, adopted in the absence of comprehensive data on the relative risks to organs and tissues from exposures *in utero*. ICRP Publication 90 (ICRP, 2003b) concluded that there are insufficient data to be able to make recommendations of specific w_T values for prenatal radiation exposures.

A particular issue in the calculation of effective dose is the assessment of the dose to remainder tissues.

In Publication 26, the "remainder" tissue was assigned a weighting factor of 0.30. The dose equivalent to the "remainder" tissues was taken to be the arithmetic average of the dose to the five most highly irradiated tissues of the "remainder" by allocating a w_T value of 0.06 to each of these tissues. This procedure resulted in a lack of additivity of the effective dose equivalent quantity, since the five tissues could vary from case to case.

In Publication 60, the "remainder" tissue was given a reduced weighting factor of 0.05. However, additivity was still lacking although reduced in magnitude due to Note 3 of Table A-3 (ICRP 1991). The equivalent dose for the "remainder" was given as the mean value for ten specified tissues and organs (see Table 3). The upper large intestine, formerly included in the remainder (ICRP 1991), has been taken together with the lower large intestine, to define the colon (ICRP 1995a). Publication 66 (ICRP 1994a) dealing with doses to the respiratory tract and dose coefficients for inhaled radionuclides specified that the extrathoracic airways be considered as part of the remainder.

While not detailed in Publication 60, the treatment of remainder was described in Publications 68 and 72 (ICRP 1994b, 1996). The remainder dose was defined by the mass weighted average of the radiation-weighted dose to organs and tissues of the remainder (Note 2 of Table A-3 in Publication 60). Due to the very different masses the contribution of the specified tissues and organs to the

remainder dose was very different (see Table 5). Because of its large mass,muscle received an effective weighting factor of nearly 0.05 which is not justified because of its low radiation sensitivity. For external exposure, however, the dose to the various tissues are similar (differ little from that of muscle) and hence in Publication 74 (ICRP 1996) a simple arithmetic dose averaging with no further weighting was used as an approximation (see Sect. 3.3).

The method for calculating effective dose recommended in *Publication 60* (ICRP 1991) includes provision for cases when a tissue which does not have an explicit weighting factor (w_T) receives the highest dose of all tissues. In these cases the (w_T) for remainder (0.05) is divided equally between the mass-weighted average dose to remainder tissues (i.e. the default remainder dose, see above) and the particular tissue. This is often referred to as the 'splitting rule' and cases where the rule applies are known as 'split remainder' cases. Implications of this rule are explored by Nelson (1997). The intention of the splitting rule was to provide protection, through the effective dose and its related limits, to potentially highly exposed tissues which had not been assigned a specific weighting factor. One of the drawbacks of this approach, however, is that, since the formulation of the effective dose can differ for different radionuclides, or for different external photon beam energies, effective dose is not strictly an additive quantity.

In the proposals for the new Recommendations the w_T for remainder (0.12) is divided equally between the 15 specified tissues given in Table 2, i.e. approximately 0.008 each. This value is smaller than the least value assigned to any of the named tissues (0.01). In practice this gives the arithmetic average of the doses to these 15 tissues. Since the formulation of remainder is the same in every case the system preserves additivity in effective doses which is a considerable advantage in practical radiation protection.

5 Practical Application in Radiological Protection

The dose limits in radiological protection are given in terms of radiation-weighted dose or effective dose. Both quantities cannot be measured directly and in practice they are assessed using other measurable quantities, models and computations.

5.1 Radioactivity and committed dose

Calculations of the radiation dose from internal or external exposure to radionuclides require information on the energies and intensities of the nuclear and atomic radiations emitted by the radionuclide. The data of ICRP Publication 38 (1983) has been used in ICRP publications since 1980. The strategy for preparing a database of nuclear decay data to replace Publication 38 has been outlined by Endo et al (2003; 2005). This database will be used in future calculations of dose coefficients.

The activity A of an amount of a radionuclide in a particular energy state at a given time is the quotient of dN by dt, where dN is the expectation value of the number of spontaneous nuclear transitions from that energy state in the time interval dt, that is

$$A = \frac{\mathrm{d}N}{\mathrm{d}t}. \qquad (5.1)$$

The SI unit of activity is s^{-1} with the special name becquerel (Bq), 1 Bq=1 s^{-1}

Radionuclides are frequently included in or absorbed to other solid, liquid or gaseous material as well as accompanied by stable isotopes of the same element and the amount is quantified by further quantities.

The *specific activity* a_s is given by the quotient of the activity *A* by the mass *m*, where *A* is the activity of the radionuclide in the mass *m.*

The *activity concentration* c_{nuclide} is given by the quotient of the activity *A* by the volume *V*, where *A* is the activity of the radionuclide in the volume *V*.

The quantity specifying contamination on surfaces is the *activity per unit area,* a_a, given by the quotient of the activity *A* by the area *F*, where *A* is the activity of a radionuclide distributed on the surface area *F*.

For practical reasons committed dose quantities have been introduced into radiological protection. Radionuclides incorporated in the human body irradiate the tissues over time periods determined by their physical half-life and their biological retention within the body. The committed dose from an incorporated radionuclide is the total dose expected to be delivered within a specified time period. The *committed radiation-weighted dose* $H_T(\tau)$, in a tissue or organ, T, is defined by

$$H_{\mathrm{T}}(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_{\mathrm{T}}(t)\mathrm{d}t \qquad (5.2)$$

where τ is the integration time following the intake at time t_0. The quantity *committed effective dose* $E(\tau)$ is then given by

$$E(\tau) = \sum_{\mathrm{T}} w_{\mathrm{T}} \cdot H_{\mathrm{T}}(\tau) \qquad (5.3)$$

For compliance with dose limits it is recommended that the committed dose is assigned to the year in which the intake occurred.

For workers the committed dose is evaluated over the 50-y period following the intake. The commitment period of 50 y is a rounded value considered by the Commission to be the life expectancy of a young person entering the workforce. The committed effective dose from intakes is also used in prospective dose estimates for members of the public. In these cases a commitment period of 50 years is considered for adults and for infants and children the dose is evaluated to age 70 years (ICRP, 1996a).

5.2 Occupational exposure

5.2.1 Assessment of effective dose from individual monitoring data

In practical situations assessment of effective dose is based on measured data from operational quantities (Fig. 1). Depending on the exposure situation considered (occupational or public exposure) different procedures are applied, especially for the dose assessment from external exposure.

In occupational exposure doses may arise from external and internal radiation sources. For external exposure individual dose monitoring is usually performed by measuring the personal dose equivalent $H_P(10)$ using personal dosemeters and taking this measured value as an acceptable assessment of the value of effective dose. For internal exposure the committed effective dose values are determined based on bioassay measurements of other quantities (e.g. activity retained in the body or in daily excretion – in exceptional cases the airborne activity density) and the application of appropriate conversion coefficients. However, for practical purposes the values from both kinds of quantities should be combined in the assessment of the value of total effective dose for demonstrating compliance with dose limits and constraints.

For practical purposes, the effective dose, E, assessed in the time period ΔT can in most situations of occupational exposure be estimated from operational quantities using the following formula:

$$E = H_{\mathrm{p}}(10) + \sum_{\mathrm{j}} e_{\mathrm{j,inh}}(\tau) \cdot I_{\mathrm{j,inh}} + \sum_{j} e_{\mathrm{j,ing}}(\tau) \cdot I_{\mathrm{j,ing}} \qquad (5.4)$$

where $H_{\mathrm{p}}(10)$ is the personal dose equivalent from external exposure defined by the dose equivalent at a depth of 10 mm in the body below the position where the dosemeter is worn (Section 3.4.2), $e_{j,inh}(\tau)$ is the committed effective dose coefficient for activity intakes by inhalation of radionuclide j, $I_{j,inh}$ is the activity intake of radionuclide j, by inhalation, $e_{j,ing}(\tau)$ is the committed effective dose coefficient for activity intakes of radionuclide j by ingestion, and $I_{j,ing}$ is the activity intake of radionuclide j by ingestion. In the calculation of the effective dose from specific radionuclides, allowance will need to be made for the characteristics of the material taken into the body. This might include the *AMAD* of the inhaled aerosol and the chemical form of the particulate matter to which the specified radionuclide is attached. The commitment period τ of 50 years relates to the life expectancy of a young person entering the workforce, as mentioned above. If incorporation of radionuclides through the skin or wounds occurs an additional term for the associated effective dose would have to be included in eq. (5.4).

ICRP has previously used dosimetric data (specific absorbed fractions) (Cristy and Eckerman 1987) derived using the computational model of the worker of Cristy (Cristy 1980). These models were patterned after the adult model of the Medical Internal Radiation Dose (MIRD) Committee (Snyder et al. 1978) and have been widely used in computational dosimetry over the past thirty years.

The Commission plans to adopt new computational models of an adult male and female based on medical tomographic images. The anatomy is described by voxels (3-dimensional volume elements), each identified as to the organ/tissue type within which it resides. The models, referred to as *computational phantoms*, have been designed to approximate the organ masses assigned to the reference adult male and female in *Publication 89* (ICRP 2001).

The new computational phantoms will be used to compute the mean absorbed dose, D_T, from radiation fields external to the body and the relationship of the effective dose to the operational quantities specific to the radiation field. Conversion coefficients representing the effective dose per unit fluence or air kerma as a function of radiation energy need to be calculated for various irradiation geometries and will be applicable to external exposures at the workplace. The same reference computational phantoms will also be used to derive dose coefficients for radiation-weighted dose H_T in relevant target regions as well as for effective dose.

In the assessment of committed effective doses from operational data related to an actual intake of specific radionuclide(s) or of radionuclide concentration(s) in the air at a workplace it is often useful to refer these data to derived parameters such as the Annual Limit on Intake (*ALI*) and the Derived Air Concentration (*DAC*).

The *ALI* was defined in Publication 60 (ICRP 1991, para S30) as an intake of a radionuclide which would lead to a committed effective dose of 20 mSv (the average annual limit on effective dose for workers, $E_{\text{limit,w}}$, in mSv). That is,

$$ALI = \frac{E_{\text{limit, w}}}{e} \quad , \tag{5.5}$$

where $e(\tau)$ is the corresponding committed effective dose coefficient in mSv/Bq.

The *DAC* is the activity concentration in air in Bq/m^3 of the radionuclide considered which would lead to an intake of an *ALI* (in Bq) assuming a breathing rate of 1.2 m^3 h^{-1} and an annual working time of 2000 h. Then the *DAC* is given by

$$DAC = \frac{ALI}{2400} \quad . \tag{5.6}$$

The Commission does not now give *ALI* values, as it considers that for compliance with dose limits it is the total dose from external radiation as well as from intakes of radionuclides that must be taken into account as indicated above. It is, however, noted that the *ALI* concept can be useful in various practical situations, e.g. in characterising the relative hazard of radiation sources to ensure that appropriate administrative controls are in place.

The *DAC* for inert gases which are not incorporated is limited by the effective dose arising from radiations incident on the body from the airborne activity. Thus the *DAC* is given by

$$DAC = \frac{E_{\text{limit,w}}}{\dot{e}_{sub}\ 2000} \tag{5.7}$$

where $\dot{e}_{\text{sub}}$ is the effective dose rate coefficient (effective dose rate in mSv/h per unit activity concentration in air) for submersion in an airborne cloud containing the noble gas radionuclide.

5.2.2 Dose Records

Any regulatory system will include guidance on the minimum requirements for keeping of dose records. The degree of detail and the retention period of dose records should be defined formally. It is, however, desirable to also retain records containing the supplementary information used in the interpretation of monitoring in the work place. As a general guide, and subject to regulatory requirements, dose records of individual workers should be retained for periods comparable with the expected lifetime of the individual; those containing the supplementary information should be retained for a period long enough to be available for any likely re-assessment of the dose record. Further advice on dose record keeping has been given by the International Atomic Energy Agency (IAEA, 1999).

5.3 Public Exposure

The annual effective dose to members of the public is not usually obtained by direct measurements as for operational exposure but is normally determined by environmental measurements, habit data and modelling. Thus it can be estimated from:

- Simulation of the effluent during the design period
- Effluent monitoring during the operational period
- Radioecological modelling (pathway analysis or environmental transport)

The following equation can be used to compute the annual effective dose to a reference person of age T_X

$$E(T_X) = \sum_{j,k} e_{j,k}(T_X)\, a_{j,k} + \sum_{j} e_{j,inh}(T_X)\, I_{j,inh}(T_X) + \sum_{j} e_{j,ing}(T_X)\, I_{j,ing}(T_X) \tag{5.8}$$

where the first term of the equation assesses the external component of the exposure and the next two terms the intake of radionuclides; $e_{j,k}(T_X)$ is a conversion coefficient that relates the annual effective dose to the reference person of age T_x to a unit activity density of radionuclide *j* in environmental medium *k*, $a_{j,k}$ is the activity density of radionuclide *j* in environmental medium *k* as indicated by radioecological modelling, $I_{j,ing}(T_X)$ and $I_{j,inh}(T_X)$ are the annual activity intake of radionuclide *j* by reference person of age T_X, respectively, and $e_{j,ing}(\tau, T_X)$ and $e_{j,inh}(\tau, T_X)$ are the committed effective dose coefficients for ingestion and inhalation intakes of radionuclide *j* by reference person of age T_X, respectively. As noted above, allowance need be made for the characteristics of the material taken into the body; i.e., *AMAD* of the inhaled aerosol and the chemical form of particulate matter for the specified radionuclide.

5.4 Application of Effective Dose

As already mentioned, the calculation of effective dose or corresponding conversion coefficients is based on reference values for the human body and its organs and tissues published in recent years (ICRP 2002) but not on data from individual persons. Conversion coefficients are calculated for a reference adult worker or a reference member of the public of a defined age group. Only the exposure conditions (e. g. the external radiation field and the intake of radionuclides) may be individually considered. The use of reference values for the human body and the averaging over both sexes clearly show that the quantity effective dose is not designed to provide an individual dose value for a specific person considered but for a reference person or group.

The weighting factors are also selected as mean values averaged over workers or members of the public and both genders. While effective dose includes radiation and tissue weighting factors, other individual factors which influence the risk from exposure to ionising radiation, e. g. gender, age, body mass, physiology and individual sensitivity, are not considered separately. This means that an individual risk assessment should not be based only on the value of an estimated effective dose but it needs additional considerations.

The specific dose coefficients are provided for the determination of effective doses in relation to exposures in the workplace, principally for planning purposes and for assessing normal occupational exposures. Further specific dose coefficients are used in relation to planning for discharges into the environment and for generic assessments for members of the public. These are all circumstances in which doses are expected to be lower than the dose limits.

The main use of effective dose is thus to provide a means to demonstrate compliance with dose limits as described before. In this sense effective dose is used for regulatory purposes worldwide.

In most exposure situations involving occupational exposure, especially with nearly homogeneous exposure of a human body, effective dose is used to limit stochastic effects. In the dose range below the annual exposure limit, the occurrence of most, and probably all, tissue reactions should be avoided. Only in a few cases (e. g. an acute exposure of a single organ with a low tissue weighting factor such as the skin) will the use of the annual limit on effective dose be insufficient to avoid tissue reactions.

In summary, effective dose should be used predominantly for assessing exposure and controlling stochastic effects in the low dose range for regulatory purposes.

The effective dose is not intended for use in more detailed retrospective dose assessments when more specific information on the exposure of individuals or groups of individuals is available. This will be desirable in cases of occupational exposure when doses approach or exceed the annual dose limit. In such cases the calculation of the effective dose may give a first rough estimate about the situation.If this procedure results in an effective dose above the dose limit, more

specific circumstances of the exposure and information on the individual (e. g. age, sex, body mass etc.) are needed to calculate organ and tissue doses for a critical judgement and possible risk assessment. Effective dose should also not be used for the evaluation of human exposure in epidemiological studies on risk assessment. In such cases absorbed doses to specific tissues or organs must be considered.

In cases of accidents which could give rise to tissue reactions the use of effective dose is completely inappropriate as discussed in Section 2.2. In such situations it is necessary to calculate absorbed dose and to take into account the appropriate RBE as the basis for any assessment of radiation effects and to make decisions on any actions needed.

5.5 Reference Person

In principle, effective dose is defined and estimated in a person (worker or person of the public) and it is intended for use prospectively in the protection of these persons. However, in order to provide a practicable approach for the assessment of effective dose, in particular for occupational exposure to low doses and prospective regulatory purposes, its value is calculated for standard conditions (mono-energetic radiations, standard irradiation geometries, selected chemical compounds, biokinetic behaviour of radionuclides in the body etc.) in anthropomorphic models with clearly defined geometry, including all organs specified in the definition of effective dose and all regions (including surfaces of bone mineral and airways, contents of walled organs, and volume of organs) where radionuclides might reside while in the body.

In the past calculations have been performed for external and internal exposure situations using different mathematical models such as the MIRD phantom (Snyder et al. 1969) or the Cristy age-specific phantoms (Cristy 1980, ICRP 1994b, 1996). However, a specific reference model has never been defined by ICRP or other international organisations. This will now be the case with the computational phantoms (based on voxels) described in Section 5.2.

Comprehensive guidance on the characteristics of the reference persons addressed by the Commission can be found in ICRP Publication 89 (ICRP 2003). That publication established the age and gender-specific physiological and anatomical characterization of reference persons. Physiological parameters determine, in part, the initial deposition of an inhaled aerosol and its subsequent clearance as well as the movement of ingested radionuclide through the gastro-intestinal tract. Similarly the fate of radionuclides absorbed from the respiratory and gastro-intestinal tracts is influenced by the physiological processes associated with cardiovascular, skeletal, hepatic, and renal systems and the metabolic pathways the radionuclide might enter. The age- and gender-specific physiological and metabolic processes regulate the distribution and retention of the radionuclides in the body.

Age and gender-specific values of the masses of the organs and tissues for reference persons are tabulated in Publication 89 (ICRP 2002). These data are used for computing the mean absorbed dose, D_T, in the organ or tissue T. The computational dosimetry models applicable to radionuclides residing in the body

divide the body into two distinct sets of anatomical regions: the source region and the target region.

The source regions, $\{S_i\}$, are the set of anatomical structures, within which radionuclide might reside while in the body. It should be noted that the source regions may correspond to organs or tissues, but also to the content of walled organs; e.g., the content of segments of the gastro-intestinal tract. The target regions, $\{T_i\}$, are the set of organs, tissues or tissue regions, , for which the mean absorbed dose is of interest. The spatial relationship of the source and target regions and the composition of intervening tissues define, in part, the mean absorbed dose in target tissue T. For radiations incident on the body from radioactive sources outside the body the size and position of the target tissue T influences the mean absorbed dose. Thus a three-dimensional description of the body is a necessary component of computational dosimetry.

As mentioned above the Commission has adopted new computational phantoms of the adult males and females based on medical tomographic images (computational phantoms based on voxels). The anatomy is described by voxels (3-dimensional volume elements) (Fill et al. 2004). They have been adjusted to approximate the organ masses assigned to the reference adult male and female in Publication 89 (ICRP 2002). The models will be used to compute, for a series of sources, the fraction of the energy emitted within source region S_i that is absorbed in target region T_j. Similarly the models will be used to compute the mean absorbed dose, D_T, in an organ or tissue, T, from radiation fields external to the body and the relationship of the effective dose to the operational quantities specific to the radiation field.

Calculations have shown that intake and exposure limits based on an effective dose quantity calculated from gender-averaged tissue weighting factors may lead to an underestimation of the health detriments among the female workers, by up to a factor of 2 compared to the average, in practical situations. This level of uncertainty in the use of the effective dose quantity is judged to be acceptable in view of other uncertainties inherent in radiological protection.

Thus, it is proposed that the gender- and age-averaged effective dose using the tissue weighting factors of Committee 1 should be computed in the manner previously adopted by Committee 2 in ICRP *Publication 74*. That is, the effective dose coefficient *e* is given as

$$e = w_{\text{breast}} h^F_{breast} + \sum_{T \neq \text{breast}} w_T \left[\frac{h^M_T + h^F_T}{2} \right] \quad . \tag{5.9}$$

where w_T is the tissue weighting factor for tissue T, and h^M_T and h^F_T are the radiation-weighted dose coefficients for tissue T of the male and female, respectively. In the case of gender-specific differences in cancer incidence-based relative detriment for the ovary of females (FD C-1 Appendix 2) the gender averaged w_T of 0.08 assigned to the gonads (cancer plus heritable effects) is similar to that of the female ovary (0.036) plus heritable effects (0.039). In this way the ovary of females is judged to be sufficiently protected.

In the case of the thyroid, the Foundation Document of Committee 1, Appendix 2 shows data for gender-specific, cancer incidence-based relative detriment with almost a factor 3 difference between females (0.021) and males (0.008). However, since the w_T assigned to the thyroid is given as 0.05 to allow for the high susceptibility of young children, gender-specific differences are also considered in a conservative way.

5.6 Conversion Coefficients for External Exposure

As mentioned before the protection quantities, radiation weighted dose and effective dose, are not measurable and their values are assessed using their relationship to either physical radiation field quantities, e. g. air kerma free in air, K_a, or particle fluence, Φ, or operational dose quantities. "Conversion coefficients" provide numerical links between these quantities and it is very important that an internationally agreed set of conversion coefficients is available which can be generally used in radiological protection practice in situations of occupational exposures and exposures of the public, too.

Based on the work of a joint ICRU/ICRP task group the Commissions have published reports (ICRP 1995, ICRU 1997) on "Conversion Coefficients for Use in Radiological Protection against External Radiation" which recommend a set of evaluated data of conversion coefficients for external exposure by monoenergetic photon, neutron and electron radiation under specific irradiation conditions. Most of the data used for the evaluation were calculated on the basis of MIRD-like models of the anatomy. Conversion coefficients are given for photons, neutrons and electrons incident on the human body under various irradiation geometries. In all cases, whole body exposure was assumed. For photons the mean absorbed dose in an organ or tissue per unit air kerma free in air and the effective dose per unit air kerma free in air are given, while for neutrons and electrons the doses are related to the particle fluence. Furthermore, Publication 74 (ICRP 1995) explored in detail the relationship between the protection quantity effective dose and the operational dose quantities for specific idealized irradiation exposure geometries.

With the exception of exposure to airborne noble gases, the Commission has not provided radionuclide-specific coefficients for exposures in workplaces or for exposure situations in the environment. It has also not provided age-specific coefficients for radionuclides distributed in environmental media.

5.7 Committed Effective Dose Coefficients from Internal Exposure

In the occupational setting each intake of a radionuclide during a year is assigned a committed effective dose, $E(\tau)$. Committed effective dose coefficients, e_τ, are conversion coefficients which provide numerical links between $E(\tau)$ and measurable quantities, in this case between $E(\tau)$ and the activity intake by either inhalation (e_{inh}) or ingestion (e_{ing}) of radionuclides.

The gender-averaged committed effective dose coefficient, is computed as

$$e(\tau) = w_{\text{breast}} \sum_{\text{R}} w_{\text{R}} d^{\text{F}}_{\text{R,breast},\tau} + 0.5 \sum_{\text{T} \neq \text{breast},} w_{\text{T}} \sum_{\text{R}} w_{\text{R}} \left(d^{\text{F}}_{\text{R,T},\tau} + d^{\text{M}}_{\text{R,T},\tau}\right) \quad (5.10)$$

where w_{T} are the tissue weighting factors, w_{R} are the radiation weighting factors, and $d^{\text{F}}_{\text{R,T}}$ and $d^{\text{M}}_{\text{R,T}}$ are the committed absorbed dose coefficients for radiation R in target tissue T for the female and male, respectively, and τ is the commitment period typically taken as 50 years for workers. The first term is limited to the female breast, and the summation term includes the gonadal target tissues (ovaries of the female and testes of the male). The committed absorbed dose coefficients for the female and male are based on the gender-specific physiologic, anatomic and biokinetic parameters of the reference adult females and males. In addition, the dosimetric parameters in the evaluation of the mean absorbed dose in tissue T are derived for gender-specific computational phantoms discussed above.

The contribution of the remainder tissue to the effective dose is derived by applying the tissue weighting factor for this group of tissues to the arithmetic average radiation-weighted dose among tissues not assigned an explicit tissue weighting. Since the intake of radionuclides is to be evaluated using effective dose coefficients, as noted in the introduction, there exists no problem regarding additivity.

5.8 Collective Dose

The dosimetric quantities for radiological protection discussed above refer to individual persons. However, the task of radiological protection is not only to protect individual persons but also to optimise and reduce the radiation exposure of groups of occupationally exposed persons or of the public. For this purpose ICRP has introduced the collective dose quantities (ICRP 1977; 1991) which should be used and seen as an instrument for optimisation. These quantities take account of the group of persons which are exposed to radiation from a source and the period of exposure. They are obtained by multiplying the number of exposed persons with the average dose to the exposed persons from a source. The specified quantities have been defined as the collective equivalent dose, S_{T}, which relates to a tissue or an organ T, and the collective effective dose, S (ICRP 1991). The special name of the unit of these collective dose quantities is the man sievert (man Sv).

The collective doses from radioactive materials in the environment were formulated in ICRP Publication 60 as the integral over doses received by the population (Para A34). The Commission formulated both the collective equivalent dose and the collective effective dose. Since the intent of the collective quantities was to serve as an instrument in optimisation of radiological protection and hence to facilitate cost-benefit analysis it is proposed that only the collective effective dose is retained in the present system.

The extensive definition as described above has led people to misuse collective doses for summing up radiation exposures for a wide range of doses over infinite time periods and large geographical regions and to calculate on this basis radiation-related detriments. However, this is only possible if there is sufficient knowledge of the risk coefficient for the detrimental radiation effects in the dose ranges which contribute to the collective dose (Kaul et al. 1987).

In this connection it has to be realized that the risk factors e.g. for carcinogenesis at low doses are obtained from the extrapolation of epidemiological data observed in dose ranges of medium and high radiation doses. The extrapolation is based on the assumption of a linear dose effect relation without a threshold (LNT concept). The Commission considers that in the low dose range the risk factors have an especially high degree of uncertainty. This is particularly the case for very low individual doses which are equivalent to small fractions of the radiation dose received from natural sources. In this sense it might be considered that individual doses of less than 10 μSv per year are negligible and might not be included into the assessment of collective dose. The use of collective dose under such conditions and for such purposes is not a valid and reasonable procedure. It had never been the intention to use collective dose in that way.

To avoid this exaggerated aggregation of individual doses in the described wide range of doses, time periods and geographical regions certain limiting conditions may need to be set. Also the time period should be stated. The collective effective dose due to individual effective dose values between E_1 and E_2 is defined as

$$S(E_1, E_2, \Delta T) = \int_{E_1}^{E_2} E \, \frac{\mathrm{d}N}{\mathrm{d}E} \, \mathrm{d}E \quad , \tag{5.11}$$

where $\frac{\mathrm{d}N}{\mathrm{d}E}$ denoted the number of individuals who experience an effective dose between E and $E + dE$ and ΔT specifies the time period within which the effective doses are summed. The number of individuals who experiences these values of the effective dose, $N(E_1, E_2)$ is

$$N(E_1, E_2) = \int_{E_1}^{E_2} \frac{\mathrm{d}N}{\mathrm{d}E} \, \mathrm{d}E \tag{5.12}$$

and the average value of effective dose $E(E_1,E_2,\Delta T)$ in the interval of individual doses between E_1 and E_2 and the time period ΔT is

$$E(E_1, E_2, \Delta T) = \frac{1}{N(E_1, E_2)} \int_{E_1}^{E_2} E \; \frac{\mathrm{d}N}{\mathrm{d}E} \, \mathrm{d}E \quad . \tag{5.13}$$

The Commission considers that values of collective dose derived from the above equations can be represented in the form of a matrix. The following aspects could be considered:

- Number of exposed individuals
- Age and gender of exposed individuals
- Range of individual doses
- Dose distribution in time
- Geographical distribution of exposed individuals.

The above equations can be extended; e.g., change in the limits of integration, to address different attributes of the collective dose.

6 Uncertainties and Judgements in Radiological Protection

In Publication 60, ICRP stressed that the assessment of radiation doses is fundamental to radiological protection although neither the dose in an organ or tissue (radiation weighted dose) nor the effective dose can be measured directly. In the evaluation of these doses models are necessary to simulate the geometry of the external exposure, the biokinetics of the intake and retention of radionuclides in the human body, and the human anatomy. Dosimetric considerations as described before are also of great importance. These models and their parameter values have been developed in many cases from experimental investigations and human studies in order to derive "best estimates" of model parameter values. It is recognized that there may be large uncertainties in the values of the parameters and in the formulation or structures of the models themselves. Some of these uncertainties have been addressed in recent publications (Leggett et al. 1998; ICRP 2002; Harrison et al. 2003; Likhtarev et al. 2003) and estimates of the illustrated variability of parameter values e.g. for physiological and anatomical characteristics have been illustrated (ICRP 2002). Such variations of parameter values are of particular significance with respect to the models necessary for dose assessments from internal exposure.

The assumed exposure-geometry model and the use of the biased nature of the operational quantities may be a major source of uncertainty in the assessment of external exposures.

Risk factors for stochastic effects, from which w_R and w_T values are derived, have been obtained from epidemiological and experimental radiobiological data in the medium and higher dose ranges. The risk factors for the lower dose ranges important for radiobiological protection as well as the concept of effective dose, are based on extrapolation from the measured data in the higher dose ranges using the linear no threshold model (LNT). This model is an assumption which has not scientifically been proven. It is considered to be the most appropriate interpretation of current data and undertanding of radiation effects but which also introduces a high degree of uncertainty especially in relation to exposures at low doses and low dose rates (UNSCEAR 2000). There are good indications for such a dose response from experimental cellular and animal data as well as from epidemiological studies. The assumed linearity and additivity are necessary conditions for the concepts used in radiological protection in the low dose

ranges, especially for the use of effective dose, as described in previous sections.

The uncertainties which are accompanied with the assessment of radiation doses and health detriments have been mentioned and discussed already at various points of this document. Some of the more important circumstances are:

- The heterogeneity of energy deposition within tissues in the low dose ranges of external as well as particularly of internal exposures,
- The heterogeneous distribution of radionuclides in organisms and in tissues which is especially problematic when considering ionising particles with short ranges such as alpha-particles.
- - For dose assessments from internal exposures the biokinetic models and their parameter values are variable dependent on the specific conditions. Frequently animal data have to be used and to be extrapolated to humans. Also human populations may vary worldwide on ethnic grounds with respect to physiological and other parameters (ICRP 2002). Variability can become especially large when radioecological models are used to assess concentrations of radionuclides in food and drink, and hence intakes from habit data as the parameters are frequently very uncertain.
- The RBE values which are important for the definition of the w_R-values vary dependent on experimental design. Again frequently the values rely on animal and in vitro data.
- The target cells for the induction of cancer and their location in tissues are unclear. The dose response in the low dose range for stochastic effects, the mode of extrapolation and the LNT concept are uncertain.
- For the estimation of health detriments gender averaging is performed.

The degree of uncertainty varies for the various parameters and the circumstances in defined situations. Therefore it is not possible to give general values but considerations of this kind should be and have been made for special cases and should be included in proper evaluations (CERRIE 2004, ICRP HAT model). In general it can be said that uncertainties for assessments of radiation doses from internal exposures including the biokinetics of radionuclides are larger than those from external exposures (CERRIE 2004).

ICRP is aware of these uncertainties and efforts are undertaken to critically evaluate and to reduce them wherever possible. However, for prospective dose assessments in regulatory processes the ICRP takes the position that the dosimetric models, as well as the parameter values, that the Commission recommends for determining doses from quantitative information about radiation fields at working places and in the environment or from intakes of radionuclides, should be taken as reference models and values which are not subject to uncertainty. Equally the Commission considers that the dosimetric models and parameter values which are needed for the purpose of recommending dose limits or constraints are defined as reference data and, therefore, are not uncertain. Nevertheless, these models and values are re-evaluated periodically and may be changed by ICRP in due time on the basis of such evaluations when new scientific data and information are available.

It should be noted that the dosimetric models, conversion coefficients and other parameters recommended by the Commission have been developed principally

for planning and assessing normal occupational exposures, for compliance of dose limits, planning for discharges into the environment and for generic assessments of doses. These are circumstances in which doses are low (Section 5.3). At higher doses, for example following accidental exposures, or for epidemiological studies, more specific information on the individual and the exposure conditions are needed. In such situations all sources of uncertainty should be taken into consideration including individual anatomical and physiological data, specific information on radionuclide source-term and biokinetics and the direction of radiation fields in relation to external exposure.

In conclusion it should be stressed again: The described reference values for models and parameters should be predominantly used for prospective radiological protection purposes. It is not especially valid to use these models and parameter values for retrospective dose assessments. They are not intended for use in the detailed estimation of specific individual human exposures and risks or to use these methods for epidemiological studies without careful consideration of the uncertainties and limitations of the models and values. This limitation of usage for prospective assessments only must be especially considered with respect to effective dose. For the judgement of individual cases absorbed doses to organs or tissues should be used with the most appropriate biokinetic parameters, biological effectiveness of the ionising radiation and risk factor data. In these cases uncertainties should be taken into consideration.

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8 Glossary

Absorbed Dose, *D*

the fundamental dose quantity given by

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

where $\mathrm{d}\bar{\varepsilon}$ is the mean energy imparted by ionising radiation to the matter in a volume element and d*m* is the mass of the matter in this volume element. The SI unit for absorbed dose is joule per kilogram (J kg^{-1}) and its special name is gray (Gy).

Activity, A

the number of nuclear transformations occurring in a given quantity of material per unit time. The special unit of activity is the becquerel (Bq).

Annual Limit on Intake (ALI)

the activity of a radionuclide which taken into the body alone would irradiate a person result in a committed effective dose, represented by reference person, to the annual dose limit set by the ICRP for each year of occupational exposure.

Becquerel (Bq)

the special name for the SI unit of activity, 1 Bq = 1 s^{-1} (≈ 2.7 x 10^{-11} Ci).

Biological Half-Life

the time required for a biological system to eliminate, by natural processes, half the amount of a substance, (eg. radioactive material) that has entered it.

Collective Dose

see collective effective dose

Collective Effective Dose, *S*

the sum of effective doses of a group of persons who obtained radiation exposures of effective dose values between E_1 and E_2 from a specified source and time period ΔT is

$$S(E_1, E_2, \Delta T) = \int_{E_1}^{E_2} E \, \frac{\mathrm{d}N}{\mathrm{d}E} \, \mathrm{d}E$$

where $\frac{\mathrm{d}N}{\mathrm{d}E}$ denoted the number of individuals who experience an effective dose between *E* and *E* + d*E* and ΔT specifies the time period within which the effective doses are summed. The number of individuals who experiences these values of the effective dose, $N(E_1, E_2)$ is

$$N(E_1, E_2) = \int_{E_1}^{E_2} \frac{\mathrm{d}N}{\mathrm{d}E} \, \mathrm{d}E$$

and the average value of effective dose $E(E_1,E_2)$ in the interval of individual doses between E_1 and E_2 and the time period ΔT is

$$E(E_1, E_2, \Delta T) = \frac{1}{N(E_1, E_2)} \int_{E_1}^{E_2} E \ \frac{\mathrm{d}N}{\mathrm{d}E} \, \mathrm{d}E \quad .$$

The unit of the collective effective dose is man sievert (man Sv).

Committed Effective Dose, $E(\tau)$

the sum of the products of the committed organ or tissue radiation weighted doses and the appropriate organ or tissue weighting factors (w_T), where τ is the integration time in years following the intake. The commitment period is taken to be 50 years for adults, and to age 70 years for children.

Committed Radiation-Weighted Dose, $H_T(\tau)$

the time integral of the radiation weighted dose rate in a particular tissue or organ that will be received by an individual following intake of radioactive material into the body by a reference person, where τ is the integration time in years

Derived Air Concentration (DAC)

equals the ALI (of a radionuclide) divided by the volume of air inhaled by a reference person in a working year (ie. 2.4 x 10^3 m^3). The unit of DAC is Bq m^{-3}.

Effective Dose, E

the sum of the radiation weighted doses in all specified tissues and organs of the body, given by the expression:

$$E = \sum_{\mathrm{T}} w_{\mathrm{T}} H_{\mathrm{T}}$$

$$E = \sum_{\mathrm{T}} w_{\mathrm{T}} \sum_{\mathrm{R}} w_{\mathrm{R}} D_{\mathrm{T,R}} \quad ,$$

where H_T is the radiation weighted dose in a tissue or organ, T, and w_T is the tissue weighting factor for tissue or organ T.

Gray (Gy)

the special name for the SI unit of absorbed dose: 1 Gy = 1 J kg^{-1}.

Intake

activity that enters the body through the respiratory tract or gastrointestinal tract from the environment.

- Acute Intake
  a single intake by inhalation or ingestion, taken to occur instantaneously.

- Chronic Intake
  an intake over a specified period of time.

Kerma, *K*

the quotient of the sum of the kinetic energies, dE_{tr}, of all charged particles liberated by uncharged particles in a mass d*m* of material and the mass d*m* of that material.

$$K = \frac{\mathrm{d}E_{\mathrm{tr}}}{\mathrm{d}m}$$

Kerma is defined as a non-stochastic quantity and dE_{tr} is, therefore, seen to be the expectation value of the sum of the kinetic energies. The SI unit for kerma is joule per kilogram (J kg^{-1}) and its special name is gray (Gy).

Linear energy transfer (LET)

a measure of the ability of biological material to absorb ionising radiation; the radiation energy lost per unit length of path through a biological material. In general, the higher the LET value, the greater is the relative biological effectiveness of the radiation in that material.

Mean Absorbed Dose in a tissue or organ T, D_T

the absorbed dose D_T, averaged over the tissue or organ T,which is given by

$$D_{\mathrm{T}} = \frac{\varepsilon_{\mathrm{T}}}{m_{\mathrm{T}}}$$

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.

Operational Quantities

these are used in monitoring and practical applications for investigating the situations involving external exposure and intakes of radionuclides and assessing values of protection quantities.

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Particle Fluence, *Φ*

the *fluence*, *Φ*, is the quotient of d*N* by d*a*, where d*N* is the number of particles incident on a small sphere of cross-sectional area da, thus

$$\phi = \frac{\mathrm{d}N}{\mathrm{d}a}$$

Protection Quantities

values that ICRP has developed for radiological protection that allow quantification of the extent of exposure to ionising radiation from both whole and partial body external irradiation and from intakes of radionuclides.

Radiation Quality

a term used to describe the fact that different radiations have different levels of biological effect. It is known to be correlated with the microdosimetric energy deposition pattern.

Radiation-Weighted Dose, H_T,

the radiation-weighted dose, H_T, (former term equivalent dose) in a tissue or organ T is given by:

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

where $D_{T,R}$ is the mean absorbed dose from radiation R in a tissue or organ T and w_R is the radiation weighting factor. Since w_R is dimensionless, the unit for the radiation-weighted dose is the same as for absorbed dose, J kg^{-1}, and its special name is sievert (Sv).

Radiation Weighting Factor, w_R

the radiation weighting factor, w_R, is a dimensionless factor to derive the radiation weighted dose from the absorbed dose averaged over a tissue or organ and is based on the quality of radiation (ICRP 1991).

Reference Person

a person with the anatomical and physiological characteristics defined in the report of the ICRP Task Group on Reference Man (ICRP Publication 89, 2001).

Reference Value

the value of a parameter recommended by ICRP for use in a biokinetic model in the absence of more specific information, ie. the exact value used to calculate the dose coefficients presented in the report. Reference values may be specified to a greater degree of precision than that which would be chosen to reflect the certainty with which the value is known, in order to avoid the accumulation of rounding errors in a calculation.

Sievert (Sv)

the special name for the SI unit of radiation weighted dose, former term equivalent dose, effective dose and the operational dose quantities: 1 Sv = 1 J kg^{-1}.

Source Region $\{S_i\}$

region within the body containing the radionuclide. The region may be an organ, a tissue, the contents of the gastrointestinal tract or urinary bladder, or the surfaces of tissues as in the skeleton and the respiratory tract.

Source Tissue

tissue (which may be a body organ) which contains a significant amount of a radionuclide following intake of that radionuclide into the body.

Specific Absorbed Fraction

the fraction of energy emitted as a specified radiation type in a source tissue which is absorbed in 1 kg of a target tissue.

Specific Effective Energy (SEE ($T \leftarrow S$)i)

the energy (MeV), suitably modified for quality factor, imparted per unit mass of a target tissue (T) as a consequence of the emission of a specified radiation (R) from a single transformation ocurring in source region $\{S_i\}$ expressed as Sv $(Bq\ s)^{-1}$.

Stochastic Effects of Radiation

malignant and hereditary disease for which the probability of an effect occurring, rather than its severity, is regarded as a function of dose without threshold.

Target Tissue (T)

tissue (which may be a body organ) in which radiation is absorbed.

Tissue Reaction

effects for which the severity of the effect in affected individuals varies with the dose, and for which a threshold usually exists. Previously termed deterministic effects or non-stochastic effects.

Tissue Weighting Factor, w_T

the factor by which the radiation weighted dose in a tissue or organ T is weighted to represent the relative contribution of that tissue or organ to the total detriment resulting from uniform irradiation of the body (ICRP, 1991). It is

$$\sum_T w_T = 1 \ .$$

9 Tables

Table 1 ICRP Recommendations for Tissue Weighting Factors in Publication 26 (1977) and Publication 60 (1991)

Tissue	Tissue Weighting Factor, w_T	
	1977 Publication 26	1991 Publication 60[b,c]
Bone surfaces	0.03	0.01
Bladder		0.05
Breast	0.15	0.05
Colon		0.12
Gonads	0.25	0.20
Liver		0.05
Lungs	0.12	0.12
Oesophagus		0.05
Red bone marrow	0.12	0.12
Skin		0.01
Stomach		0.12
Thyroid	0.03	0.05
Remainder	0.30[a]	0.05
TOTAL	1.0	1.0

Notes:

a The 5 most highly irradiated other organs and tissues are included in remainder, each with a $w_T = 0.06$.

b The values have been developed from a reference population of equal numbers of both sexes and a wide range of ages. In the definition of effective dose they apply to workers, to the whole population and to either sex.

c Further footnotes in Publication 60. Table 5.2, page 68.

Table 2 Proposed Tissue Weighting Factors in new Recommendations

Tissue	w_T	$\sum w_T$
Red bone marrow, colon, lung, stomach, Remainder Tissues* (Nominal w_T applied to the average dose to 15 tissues)	0.12	0.60
Breast, Gonads	0.08	0.16
Bladder, oesophagus, liver, thyroid	0.05	0.20
Bone surface, brain, salivary glands, skin	0.01	0.04

*Remainder Tissues (15 in total)
Adipose tissue, Adrenals, Connective tissue, Extrathoracic airways[a], Gall bladder, Heart wall, Kidneys, Lymphatic nodes, Muscle, Pancreas,Prostate, SI wall, Spleen, Thymus and Uterus/cervix
[a]As defined in ICRP Publication 66, includes anterior (ET1) and posterior nasal passages, larynx, pharynx and mouth (ET2)

Table 3 Radiation Weighting Factors[1] (ICRP 1991)

Type and energy range[2]			Radiation weighting factors, w_R
Photons, all energies			1
Electrons and muons, all energies[3]			1
Neutrons, energy	<	10 keV	5
		10 keV to 100 keV	10
	>	100 keV to 2 MeV	20
	>	2 MeV to 20 MeV	10
	>	20 MeV	5
Protons, other than recoil protons, energy > 2 MeV			5
Alpha particles, fission fragments, heavy nuclei			20

1 All values relate to the radiation incident on the body or, for internal sources, emitted from the source.

2 The choice of values for other radiations is discussed in paragraph A14 in ICRP (1991).

3 Excluding Auger electrons emitted from nuclei bound to DNA (see paragraph A13 in ICRP 1991).

Table 4 Proposed Radiation Weighting Factors in new Recommendations

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons and muons	1
Protons	2
Alpha particles, fission fragments, heavy nuclei	20
Neutrons	A continuous curve depending on neutron energy is recommended (see Figure 2 and equation 4.7)

10. Figures

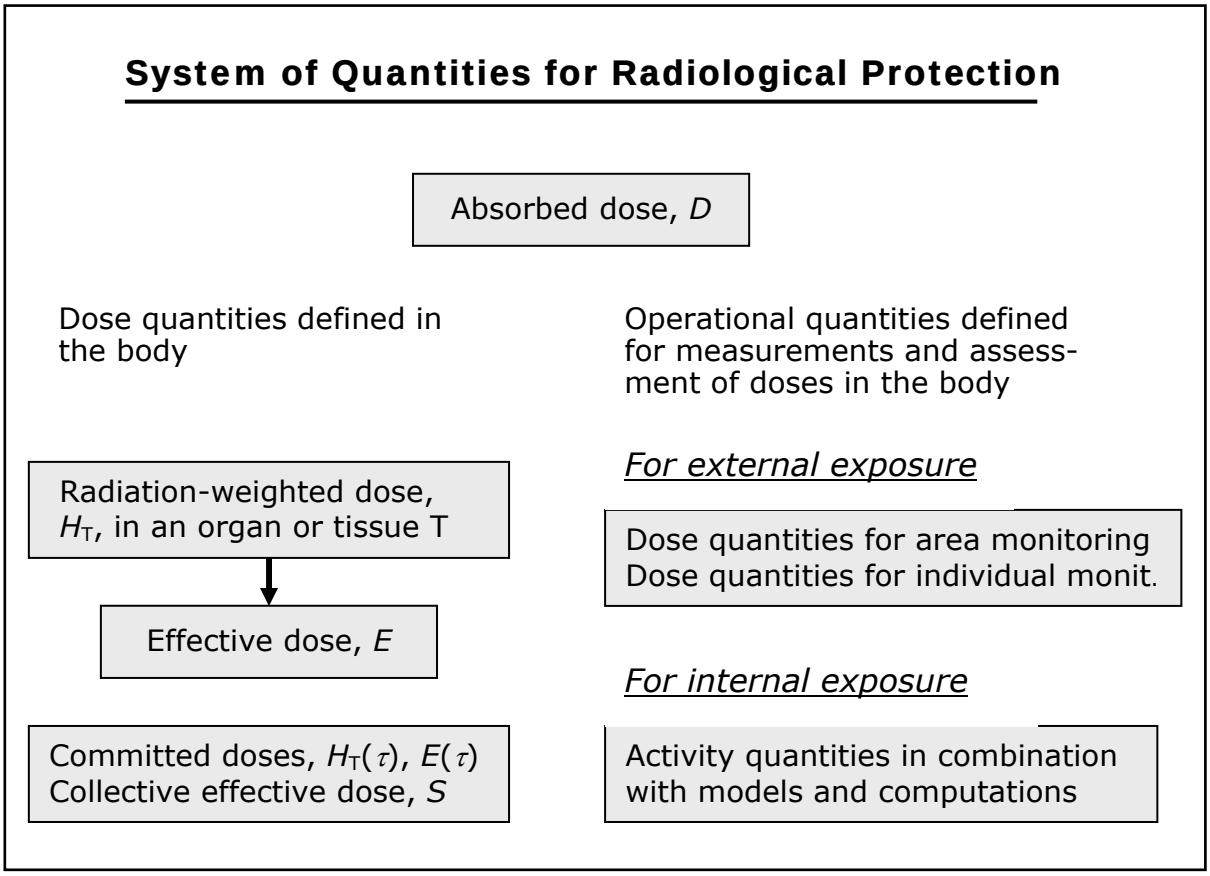

Figure 1. System of quantities for use in radiological protection

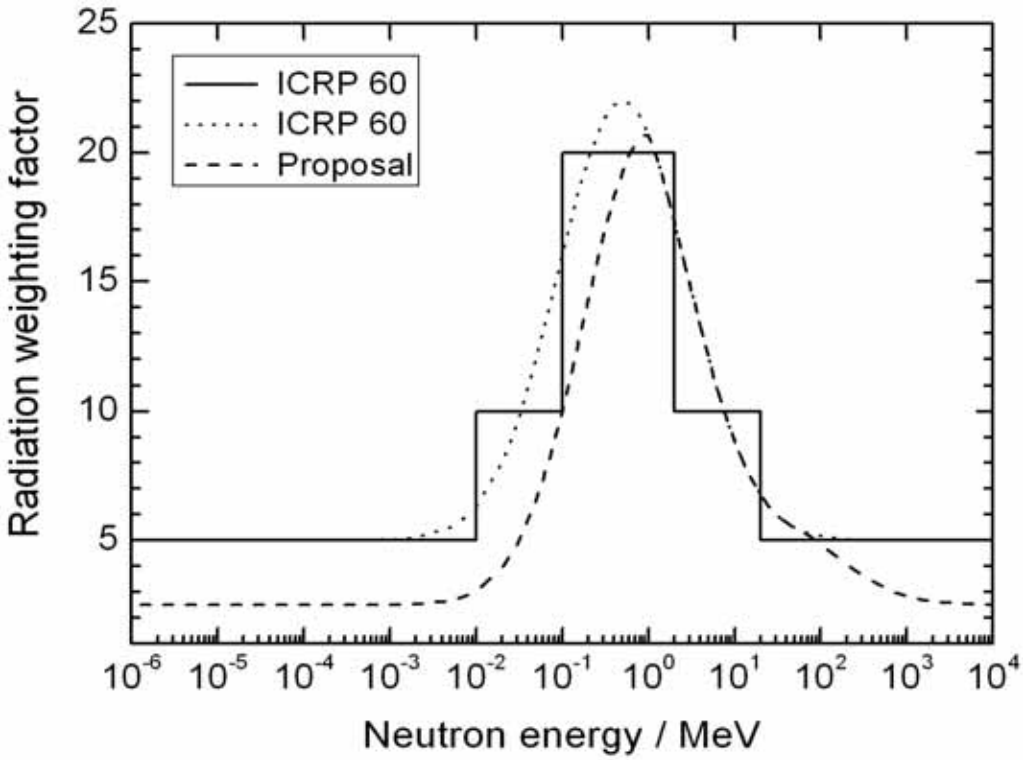

Figure 2. Radiation weighting factor, w_R, for neutrons versus neutron energy. Step function and continuous function given in Publication 60 (ICRP 1991) and function proposed in this report.