THE ICRP PROTECTION QUANTITIES, EQUIVALENT AND EFFECTIVE DOSE: THEIR BASIS AND APPLICATION

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Equivalent and effective dose are protection quantities defined by the The International Commission on Radiological Protection (ICRP). They are frequently referred to simply as dose and may be misused. They provide a method for the summation of doses received from external sources and from intakes of radionuclides for comparison with dose limits and constraints, set to limit the risk of cancer and hereditary effects. For the assessment of internal doses, ICRP provides dose coefficients (Sv Bq^{-1}) for the ingestion or inhalation of radionuclides by workers and members of the public, including children. Dose coefficients have also been calculated for *in utero* exposures following maternal intakes and for the transfer of radionuclides in breast milk. In each case, values are given of committed equivalent doses to organs and tissues and committed effective dose. Their calculation involves the use of defined biokinetic and dosimetric models, including the use of reference phantoms representing the human body. Radiation weighting factors are used as a simple representation of the different effectiveness of different radiations in causing stochastic effects at low doses. A single set of tissue weighting factors is used to take account of the contribution of individual organs and tissues to overall detriment from cancer and hereditary effects, despite age- and gender-related differences in estimates of risk and contributions to risk. The results are quantities that are not individual specific but are reference values for protection purposes, relating to doses to phantoms. The ICRP protection quantities are not intended for detailed assessments of dose and risk to individuals. They should not be used in epidemiological analyses or the assessment of the possibility of occurrence and severity of tissue reactions (deterministic effects) at higher doses. Dose coefficients are published as reference values and as such have no associated uncertainty. Assessments of uncertainties may be appropriate in specific analyses of doses and risks and in epidemiological studies.

INTRODUCTION

The International Commission on Radiological Protection (ICRP)[1,2] introduced the protection quantities, equivalent and effective dose, to facilitate the comparison of doses with dose limits and constraints. These quantities provide a method for the summation of contributions to dose and risk from external sources and radionuclides incorporated into body tissues, for the limitation of stochastic effects— cancer and hereditary effects. However, equivalent and effective dose and committed doses are often referred to simply as dose and there has been widespread misunderstanding of their intended use. There are also differences between experts on their interpretation[3].

Concerns over the use of the ICRP protection quantities are exemplified by the conclusions of a UK government committee, set up to examine the adequacy of ICRP methodology as applied to internal emitters[4]. The Committee Examining Radiation Risks from Internal Emitters (CERRIE) considered basic data on biological effects and epidemiology as well as ICRP approaches to the estimation and limitation of doses and risks. Most members of CERRIE agreed that ICRP makes appropriate use of current knowledge. However, two

important conclusions were that ICRP should clarify and elaborate its advice on the use of the quantities, equivalent and effective dose, and that more attention should be paid to uncertainties in dose and risk estimates and their implications[4].

In the ICRP scheme, doses are calculated separately for adults, children of different ages and for *in utero* irradiation of the embryo and fetus[5,6]. However, a single set of tissue weighting factors (w_T) is used to represent the contributions of doses to individual organs and tissues to the overall risk of cancer and hereditary effects[2,7]. These w_T values are chosen as averaged and rounded values on the basis of age- and gender-specific risk data. Adult organ and tissue doses will soon be calculated separately for males and females using newly developed reference anatomical models[7–9]. The male and female organ and tissue doses will be averaged before applying w_T values in the calculation of effective dose. Age and gender differences in doses and risks require that a clear rationale be given for both male/female dose averaging and the use of a single set of w_T values.

There are uncertainties associated with each step of the calculation of the ICRP protection quantities: in the use of biokinetic and dosimetric models and in the data underlying the choice of radiation weighting factors and w_T values[4]. However, the ICRP is clear that the protection quantities are not

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subject to uncertainties but are reference values (www.icrp.org). Again, a clear explanation is needed.

New ICRP recommendations will be supported by detailed discussion of the calculation of equivalent and effective dose and on their application[7]. This paper concentrates on these issues, outlining the ICRP methodology, including recent developments, and examining the basis for the approaches adopted. Consideration is given to situations in which the use of equivalent and effective dose is inappropriate and in which evaluation of uncertainties might be important.

CALCULATION OF EQUIVALENT AND EFFECTIVE DOSE

Absorbed, equivalent and effective dose

The ICRP publishes dose coefficients (Sv Bq^{-1}) for intakes of individual radionuclides, giving both equivalent doses to individual organs and tissues, and effective dose[5,6]. The steps in their calculation can be summarized as follows:

- The use of biokinetic models to represent the distribution and retention of radionuclides in body organs and tissues and calculate the total number of disintegrations occurring in each 'source region'.
- The use of dosimetric models to calculate absorbed doses, D (Gy), to each target organ or tissue from disintegrations occurring in each source region.
- The use of radiation weighting factors, w_R, to take account of the relative biological effectiveness of different radiation types, converting absorbed doses to equivalent doses (Sv). The equivalent dose, $H_{T,R}$, in tissue or organ T due to radiation R, is given by:

$$H_{T,R} = w_R D_{T,R}$$

The total equivalent dose to an organ or tissue, H_T, is the sum of $H_{T,R}$ over all radiation types:

$$H_T = \sum_R H_{T,R}$$

- The use of tissue weighting factors, w_T, to represent the contribution of individual organs and tissues to overall detriment from cancer induction and hereditary effects, summing weighted equivalent doses to give effective dose (Sv):

$$E = \sum_T w_T H_T$$

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

The use of effective dose allows the summation of doses from different radionuclides and from external sources and comparison with dose limits set on the basis of risk relating to whole body radiation exposure. Equivalent and effective doses are commonly integrated over a 50-year period for adults and to age 70 years for children and the resulting values are referred to as committed doses. The steps in the ICRP scheme are examined next.

Biokinetic and dosimetric models

ICRP biokinetic models consider intakes by ingestion and inhalation by adults and children[5,10]. Doses to the fetus following maternal intakes have been calculated[6] and also doses to infants from radionuclides transferred to breast milk[11]. Models of the alimentary and respiratory tracts are used to define the movement of radionuclides within these systems, resulting in absorption to blood and/or loss from the body. ICRP has recently developed a new model of the alimentary tract, which includes gender-dependent transit times for adults[12]. The behaviour of radionuclides absorbed to blood is described by element-specific systemic models that range in complexity from very simple models that assume uniform whole-body distribution (e.g. hydrogen and caesium) to multi-compartment recycling models that take account of movement within and between body organs and tissues (e.g. strontium, lead, uranium and plutonium). The most complex models are those developed for the bone-seeking alkaline earth and actinide elements. The representation of physiological reality in these models includes movement between organs and tissues via the circulation. In addition, the recycling models were designed to fit excretion data and can be used for bioassay interpretation. Simpler models for other elements are less suitable for this purpose.

Dose calculations involve the use of nuclear decay data[13] and anthropomorphic phantoms that describe geometric relationship between different tissues and organs. There are two main types of phantom—mathematical phantoms that approximate the sizes and shapes of organs mathematically[14] and voxel phantoms that use data for real individuals obtained using computed tomography or magnetic resonance imaging. ICRP currently uses mathematical phantoms that have been developed for adults and children of different ages[14], and for the pregnant woman and fetus for each trimester of pregnancy[6]. Voxel phantoms for a reference adult male and female are currently being developed for use by ICRP[8,9], adjusting data from scanned images for consistency with ICRP reference data for the body mass and related characteristics of adult

males and females[15]. Voxel phantoms for children will also be developed.

Doses from 'cross-fire' radiation between source and target tissues are important for penetrating photon radiation. For 'non-penetrating' alpha and beta particle radiations, energy will in most cases be largely deposited in the tissue in which the radionuclide is deposited. However, source and target considerations are taken into account for alpha and electron emissions in a number of important cases. These include:

- doses to target cells in the walls of the bronchiolar airways from radionuclides in the mucus layer within the airway;
- doses to target regions in the gut from radionuclides in the lumen[12];
- doses to cells adjacent to inner bone surfaces (taken to be a 10-μm layer) and all red marrow from radionuclides on bone surfaces and within bone mineral;
- cross-fire irradiation between fetal tissues for electron emissions [6].

For all dose calculations, radionuclides are assumed to be uniformly distributed throughout source regions, although these can be whole organs (e.g. liver) or a thin layer within a tissue (e.g. bone surfaces). Similarly, target cells are assumed to be uniformly distributed throughout target regions that vary in size from whole organs to layers of cells.

Dose coefficients for children tend to be greater than for adults, depending on the radionuclide. For example, for ingestion of ^{239}Pu, the dose coefficient for a 3-month-old infant is 17 times greater than for adults, while for ^{137}Cs the difference is a factor of 1.5. Differences between female and male adults, calculated using new anatomical models, will generally be smaller than between children and adults.

Radiation weighting factors

Different types of radiation are known to vary in their effectiveness in causing biological effects including cancer[2,15]. These differences can be related in principle to the three-dimensional structure of ionisation tracks produced by charged particles traversing tissue volumes of interest, containing sensitive cellular targets including chromosomal DNA. The linking of biological effects to track structure is one of the central research goals in the field of microdosimetry. Currently, a simple one-dimensional indicator of track structure, namely the linear energy transfer (LET), is used to inform judgements on biological effects[2,15]. The two broad categories of radiation that require consideration in the context of internal dosimetry are photons and charged particles, the latter including electrons and alpha particles. Photons and electrons (beta particles) are low-LET radiations, alpha particles have high LET.

In practice, the assessment of the different effectiveness of different radiations relies on data on their Relative Biological Effectiveness (RBE), defined as the ratio of the absorbed dose of a reference radiation to the absorbed dose of a test radiation required to produce the same level of effect. RBE is therefore an empirical quantity that depends on the biological system, the observed end-point and the conditions of the experiment. It is usually found to vary with dose and dose rate, increasing for high-LET radiation to a maximum value at low dose and dose rate because of a curvilinear response at higher acute doses of the reference low-LET radiation. RBE_{MAX} values are applicable to estimation of stochastic risk at low doses[15].

Low-LET radiations show differences in RBE that reflect differences in their average ionisation density. Thus, for example, low-energy beta emissions from tritium (^{3}H) decay have been shown to have RBE values of up to between 2 and 3, compared with gamma rays, for *in vitro* endpoints including cell killing, mutation and induction of chromosomal aberrations[16]. For photons, an increase in RBE with decreasing energy is supported by theoretical calculations[17] and experimental observations[18]. Thus, compared to ^{60}Co gamma rays, 29 kVp mammography X rays have higher RBE values than 220 kVp X rays by up to a factor of 4. Such RBE values have been observed for dicentric chromosome aberrations and cell transformation with mammalian cells *in vitro*[7].

Reviews of available human and animal data on RBE for alpha-emitting radionuclides, compared with low-LET reference radiations, indicate that RBE depends on the biological endpoint under consideration[15,19]. Human data that allow comment on alpha particle RBE values are consistent with values of around 10–20 for lung and liver cancer and lower values for bone cancer and leukaemia, although considerable uncertainty must attach to any numerical estimate of RBE from these data[19]. However, there is evidence from animal and *in vitro* studies of RBE values for alpha emitters of around 10 or greater for some cancer-related effects, and low values of 1–2 for leukaemia[15]. Human and animal data for bone cancer induction by alpha-emitting radionuclides suggest that there may be a threshold dose for some tumour types[15,19].

Despite differences in RBE between different low-LET radiations and observations of different alpha particle RBE values for different endpoints, ICRP calculate equivalent dose using radiation weighting factors of 1 for all low-LET radiations and 20 for alpha particles.

Tissue weighting factors

Tissue weighting factors (w_T) express the contribution of individual organs and tissues to overall detriment from cancer and hereditary effects, relating to whole body radiation exposure. Table 1 shows the values to be introduced in the new ICRP recommendations[7]. As for the current values[2], the main source of data on cancer risks is the follow-up studies of the Japanese atomic bomb survivors. The new w_T values are based on cancer incidence rather than fatality data, adjusted for lethality and loss of quality of life. Weighting for hereditary effects is now based on estimates of disease in the first two generations rather than at theoretical equilibrium. The main changes in w_T values in the new recommendations are an increase for breast (from 0.05 to 0.12), a decrease for gonads (from 0.2 to 0.08) and inclusion of more organs and tissues in a larger 'Remainder' (from 0.05 to 0.12).

Tissue weighting factors are based on values of relative detriment, calculated separately for males and females and applying to populations of all ages. These relative detriment values and corresponding absolute detriment values are given in the health effects annex of the new recommendations. The overall detriment value for females is 40% greater than for males. The largest differences for individual organs are factors of 0.4, 0.5, 2.0 and 4.2 for females compared to males, for colon, liver, lung and thyroid, respectively. In addition, breast cancer accounts for about one-quarter of the total detriment in females.

The male and female detriment and cancer incidence data tabulated by ICRP[7] apply to populations of all ages and take account of age-specific

Table 2. Life-time attributable risk of specific cancers after irradiation at different ages. Number of cases per 10^6 exposed to a single dose of 10 mGy.

Cancer site	Age at exposure (years)					
	Males			Females		
	0	20	60	0	20	60
Breast	—	—	—	1171	429	31
Colon	336	173	94	220	114	62
Liver	61	30	14	28	14	7
Lung	314	149	89	733	346	201
Thyroid	115	21	0.3	634	113	1
Leukaemia	237	96	82	185	71	57
All cancers	2563	977	489	4777	1646	586

Selected data from BEIR VII (NRC/NAS, 2006)[20].

data. The BEIR VII report[20] gives estimates of lifetime attributable risk for radiation exposure of males and females at different ages. Selected data from the report are shown in Table 2. In general, risk estimates are about double for irradiation in infancy compared with age 20 y, and ~5–6 times greater for thyroid cancer. Risks of *in utero* irradiation were considered in the context of setting tissue weighting factors by Streffer[21], with the conclusion that contributions to overall detriment could not be reliably quantified on the basis of current evidence.

USE AND MISUSE OF EQUIVALENT AND EFFECTIVE DOSE

ICRP dose coefficients are calculated using defined biokinetic and dosimetric models, including reference anatomical data for the organs and tissues of the human body. They are calculated for reference adults, children of different ages and the fetus at different stages of development. They do not take account of individual characteristics. Radiation weighting factors are chosen as a simple representation of the different effectiveness of different radiations in causing stochastic effects at low doses and dose rates. They do not take account, for example, of observed differences between low-LET radiations (e.g. photons of different energies), and of different alpha particle RBE values for different cancer types. A single set of tissue weighting factors is used to take account of the contribution of individual organs and tissues to overall detriment from cancer and hereditary effects, despite age- and gender-related differences. Doses to male and female adults will soon be calculated separately using new anatomical models, but equivalent doses to males and females will be averaged before calculation of effective dose.

Table 1. Tissue weighting factors, w_T, in new ICRP recommendations.

Organ/Tissue	Number	w_T	Total contribution
Lung, stomach, colon, bone marrow, breast, remainder[a]	6	0.12	0.72
Gonads[b]	1	0.08	0.08
Thyroid, oesophagus, bladder, liver	4	0.04	0.16
Bone surface, skin, brain, salivary glands	4	0.01	0.04

[a]The specified remainder tissues (14 in total, 13 in each gender) are: adrenals, extrathoracic tissue (ET), gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate(♂), small intestine (SI), spleen, thymus, uterus/cervix (♀).
[b]The w_T for gonads is applied to the mean of the doses to testes and ovaries.

It is clear from the approaches taken to the calculation of equivalent and effective dose that these quantities are not individual specific but relate to reference persons, to reference workers and reference members of the public of different ages. Their purpose is mainly for testing compliance with dose limits and constraints, providing a practical method for the assessment of doses received from internal exposure to different radionuclides and from external exposures. They are used in this way for regulatory purposes worldwide. Practical protection would not be improved by calculating effective dose separately for males and females and to do so would imply a degree of precision in the calculations that may be misleading. Similarly, a more complex treatment of radiation weighting or of tissue weighting for different age groups would be inconsistent with the intended purpose of the protection quantities and may again imply greater precision than is justified.

Particularly in retrospective dose assessments for occupational exposures, but also in planned exposures, information may be available that differs from the standard reference parameter values used in the calculation of dose coefficients. In such situations it may be appropriate, depending on the level of exposure, to use specific data in the assessment of intakes and calculation of doses. It is, therefore, important to distinguish between those parameter values that might be altered in the calculation of effective dose under the particular circumstances of an exposure and those values that cannot be changed under the definition of effective dose.

In the assessment of effective dose in occupational situations of exposure to radionuclides, changes may reasonably be made to assumptions regarding the physical and chemical characteristics of inhaled or ingested radionuclides to better assess exposures (i.e. intake by inhalation or ingestion). In addition, where appropriate information is available, specific biokinetic data may also be used to improve the assessment of the intake. Similarly, for environmental exposures for which specific information is available, such as the chemical form of a radionuclide in a food material, changes may be made to improve the assessment of exposure. In each of these cases, the intention is not to estimate individual doses and risks but to improve estimates of exposures and intakes in the calculation of effective dose for regulatory purposes.

For retrospective assessments of occupational doses to specific individuals in accident cases in which radiation doses could exceed limits, it may be considered appropriate to make specific individual estimates of dose and risk. Such an assessment would not be done for regulatory purposes but to provide a best estimate of risks to the individual(s) involved. Consideration might then be given to changes in dosimetric assumptions (e.g. body and organ mass) used to calculate absorbed doses, and organ-specific risk estimates relating to the age and gender of the individual and the radiation exposure. Such changes from reference parameter values are not consistent with the definition or intended use of effective dose. They would only be performed by radiation protection specialists, with the level of effort determined by the level of exposure.

Equivalent and effective dose relate to stochastic effects and are not applicable to tissue reactions (deterministic effects) occurring at higher doses. To assess the likelihood of occurrence and possible severity of tissue reactions, it is necessary to estimate absorbed doses and dose rates to organs and tissues. Radiation weighting factors applicable to stochastic effects are not relevant; RBE values for tissue reactions should be used[22,23].

Effective dose is not an appropriate quantity for use in epidemiological studies of radiation risks and the same applies generally to equivalent dose. Epidemiological analyses instead require estimates of absorbed doses to tissues and organs, taking full account, to the extent possible, of the circumstances of exposure and the characteristics of the exposed individuals in the study population. Similarly, absorbed organ and tissue doses, not effective doses, are required for calculations of probability of causation of cancer in exposed individuals.

UNCERTAINTIES

There are uncertainties associated with all aspects of the estimation of doses and risks at low doses. Uncertainties in biokinetic models and their parameter values depend on the availability of reliable data and often include the applicability of animal data to humans. Dosimetric uncertainties include the treatment of source and target distributions within tissues for radionuclides with short-range emissions (see above). RBE values are often difficult to assess from available animal and human data and the applicability of *in vitro* endpoints to cancer in humans may be questionable. Uncertainties in estimates of cancer risks relate to assumptions regarding the transfer of risks across populations, the validity of different risk models, the use of a dose and dose-rate effectiveness factor (DDREF) and the use of a linear dose–response relationship at low doses. Assessments of uncertainties in risk estimates and in radionuclide doses have been published but there is as yet no comprehensive information on uncertainties for a range of radionuclides[4,24]. The importance of considering uncertainties where appropriate has, however, been recognised by ICRP and others[4,7,12].

Because ICRP dose coefficients (values of dose per unit intake) are calculated as reference values, applying to reference persons, they are not regarded as subject to uncertainty (icrp.org.uk). Thus, in

general, regulatory compliance is determined using point estimates of effective dose with no consideration of uncertainties. An exception may be occupational exposures in which uncertainties are assessed for the exposure conditions. In such a case, a range on intake would result in a range on effective dose, calculated using reference dose coefficients. Similarly, uncertainties in effective doses to members of the public might be related to a probability distribution on concentrations of a radionuclide in a food material.

As discussed earlier, for retrospective assessments of occupational doses to specific individuals in accident cases in which radiation doses could exceed limits, it may be considered appropriate to make specific individual estimates of dose and risk. In such cases it may well be appropriate to estimate uncertainties as well as central values of absorbed doses, and organ-specific risk estimates relating to the age and gender of the individual and the radiation exposure. Assessments of uncertainties in dose and risk estimates for members of the public, including children, might similarly be of value in situations where the effective dose is assessed to be a significant fraction of the dose limit or constraint. Such estimates of uncertainties may help to inform judgements on the optimisation of protection. Assessments of uncertainties in absorbed doses are routinely made in epidemiological studies.

CONCLUSIONS

It is important to recognise that the ICRP protection quantities, equivalent and effective dose, do not relate to individuals but to reference persons. They are calculated using reference models and defined radiation and tissue weighting factors. They provide a method for the summation of doses from external radiation and from radionuclides that may differ substantially in their organ distribution and timecourse of dose delivery. The purpose of the protection quantities is mainly to test compliance with dose limits and constraints, set to limit the occurrence of stochastic effects. Practical protection would not be improved by calculating effective dose separately for males and females and to do so might give a misleading impression of the precision of these quantities. Similar considerations apply to the possibility of more complex treatments of radiation weighting or effective doses for different age groups.

In the assessment of effective dose in occupational situations of exposure to radionuclides, changes may be made to assumptions regarding the physical and chemical characteristics of inhaled or ingested radionuclides to better assess exposures. In addition, where appropriate information is available, specific biokinetic data may also be used to improve the assessment of the intake. Similarly, for environmental exposures for which specific information is

available, such as the chemical form of a radionuclide in a food material, changes may be made to improve the assessment of exposure. In each of these cases, the intention is not to estimate individual doses and risks but to improve the estimate of exposure in the calculation of effective dose for regulatory purposes.

Equivalent and effective dose are not applicable to detailed assessments of dose and risk to individuals. For such evaluations, absorbed doses to organs and tissues should be used and may be estimated specifically for the individual, changing biokinetic and dosimetric assumptions. Best available information on RBE and age- and gender-specific risk data would also be used. Absorbed doses should also be used in epidemiological analyses. Evaluation of the occurrence and severity of tissue reactions (deterministic effects) require the consideration of doses and dose rates to organs and tissues and RBE data applicable to the specific effects.

ICRP dose coefficients are reference values that are not subject to uncertainty[7]. Thus, in general, regulatory compliance is determined using point estimates of effective dose with no consideration of uncertainties. Consideration of uncertainties might be appropriate in retrospective assessments of dose and risk to individual workers with high assessed effective doses. Assessments of uncertainties in dose and risk estimates for members of the public, including children, might similarly be of value in situations where the effective dose is assessed to be a significant fraction of the dose limit or constraint. Such estimates of uncertainties may be of value in the optimisation of protection.

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