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Annals of the ICRP

ICRP PUBLICATION XXX

The Use of Effective Dose as a Risk-related Radiological Protection Quantity

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Use of Effective Dose

ICRP Publication XXX

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GUEST EDITORIAL

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Abstract

The protection quantity ‘effective dose’ (E) was developed by ICRP for use in the protection of workers and the public. In these applications, it is used as a risk-adjusted dosimetric quantity to optimize protection from stochastic effects, principally cancer, comparing planned or received doses with constraints, reference levels and limits expressed in the same quantity. Its use allows all radiation exposures from external and internal sources to be considered together and summed, relying on the assumptions of a linear non-threshold dose-response relationship, equivalence of acute and chronic exposures at low doses, and equivalence of external and internal exposures. Considering exposures incurred during medical procedures, E is of practical value for comparing: doses from different diagnostic examinations and interventional procedures; the use of similar technologies and procedures in different hospitals and countries; and the use of different technologies for the same medical examination, provided that the representative patients or patient populations for which the effective doses are derived are similar with regard to age and sex. However, as stated in the 2007 Recommendations (*Publication 103*), “... risk assessment for medical diagnosis and treatment ... is best evaluated using appropriate risk values for the individual tissues at risk and for the age and sex distribution of the individuals undergoing the medical procedures”.

Publication 103 provides detailed explanation of the purpose and use of E and of equivalent dose to individual organs and tissues. However, questions have arisen regarding practical applications, highlighting a clear need for further guidance on specific aspects. This publication draws on the explanations provided in Publication 103 and emphasises that E has proved a valuable and robust quantity for use in the optimisation of protection and setting of control criteria. Proposals are made that:

- a) Confusion will be avoided if equivalent dose is no longer used as a protection quantity but regarded as an intermediate step in the calculation of E . It will be more appropriate for limits for the avoidance of deterministic effects for the hands and feet, lens of the eye, and skin, to be set in terms of the scientific quantity, absorbed dose (Gy) rather than equivalent dose (Sv). This change would not require changes to the numerical values of dose limits.
- b) E is in widespread use in medical practice as a rough indicator of risk. It is made clear in this report that while doses incurred at low levels of exposure may be measured or assessed with reasonable accuracy, the associated risks are uncertain. However, bearing in mind the uncertainties associated with risk projection to low doses, it is considered reasonable to use E as a rough indicator of possible risk, with the additional consideration of variation in risk with age, sex and population group. Adjustments for the body mass of individual is discouraged as differences in dose and the associated risk are small in comparison with uncertainties in risk projection. Use of E in this way is not a substitute for risk analysis using best estimates of organ doses, appropriate information on the relative effectiveness of different radiation types, and age-, sex- and population- specific risk factors, with consideration of uncertainties.

PREFACE

Experience has shown that the quantity ‘effective dose’ which has been defined and introduced by ICRP for risk management purposes, i.e. for risk limitation and optimisation, is widely used in radiological protection and related fields beyond its original purpose, incorrectly in some cases. Useful guidance on restrictions for the use of the quantity is provided in the 2007 Recommendations (*Publication 103*). However, ICRP has recognised the need to expand this guidance with an important focus being medical exposures.

The Task Group has made use of a draft report produced by a Working Party chaired by John Cooper. Task Group membership has included members of Committees 1, 2, 3 and 4.

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MAIN POINTS

- 1) Effective dose (E) in sievert (Sv) is accepted internationally as the central radiological protection quantity, providing a risk adjusted measure of total body dose from external and internal sources in relation to stochastic risks of cancer and hereditary effects, expressed in terms of detriment.
- 2) E has proved to be a valuable and robust quantity for use in the optimisation of protection and setting of control criteria: limits, constraints and reference levels.
- 3) The use of E relies on the reasonable assumption of a linear non-threshold dose-response relationship between dose and risk at low doses, and the equivalence of effect of acute and chronic exposures, and of internal and external exposures.
- 4) Mean absorbed dose averaged over organs and tissues is the primary scientific quantity from which E is calculated. Absorbed dose in gray (Gy) should be used to set limits on organ/tissue doses to prevent tissue reactions (deterministic effects).
- 5) Equivalent dose to organs and tissues, obtained by multiplying absorbed dose by radiation weighting factors (w_R) to account for the relative effectiveness of different radiation types in causing stochastic effects, can be seen as an intermediate step in the calculation of E and it is proposed that its use as a separate protection quantity should be discontinued.
- 6) Nominal stochastic risk coefficients and corresponding detriment values, to which E relates, are calculated as averages from sex-, age-, and population- specific values, to provide internationally applicable values for all workers (18-65y) and the whole population. Tissue weighting factors (w_T) used in the calculation of effective dose are a simplified representation of relative detriment values, relating to detriment for the whole population.
- 7) E is calculated for sex-averaged Reference Persons of specified ages. The Publication 103 definition includes the specification of reference male and female anatomical models for radiation transport calculations. While exposures may relate to individuals or population groups, E is calculated for Reference Persons exposed in the same way.
- 8) Although E will generally be used at doses below 100 mSv, its use exceptionally in accident situations at doses of a few 100s mSv is reasonable, noting that the possibility of occurrence of deterministic effects should be considered at such doses if a significant contribution is made by radionuclides concentrated in specific tissues/organs.
- 9) ICRP provides effective dose coefficients for situations of external and internal exposures of workers and members of the public, and for radiopharmaceutical administrations to patients, as reference values for use in prospective and retrospective dose assessments.
- 10) Revision in dose coefficients due to changes made in ICRP recommendations, including changes to weighting factors, should not require the revision of previous dose assessments.

- 11) Reference dose coefficients are provided for particular circumstances of exposure, including specific chemical and physical forms of ingested and inhaled radionuclides. Better information on the exposure should be used if available and if the assessment warrants its use.
- 12) *E* is generally calculated for annual exposures, relating to external dose received in the year and committed dose from internal exposures, where committed dose is integrated over a 50y period for workers and to age 70y for members of the public. This procedure introduces an element of conservatism for long-lived radionuclides with long biological half-times but in many cases doses from radionuclides will be delivered within the year or over a few years after intake.
- 13) Although effective dose coefficients are provided for a number of age groups of children, it is normally sufficient in public dose assessments to use only the groups 1y, 10y and adults.
- 14) Effective dose coefficients for the embryo/fetus following intakes of radionuclides are provided for comparison with dose for other age groups to ensure protection of the fetus, showing that it is only in the case of a few radionuclides that fetal doses may need in some circumstances to be considered.
- 15) The use of constraints and reference levels that apply to all workers and all members of the public, together with optimisation, provides a pragmatic and workable system of protection that recognises age- sex-, and population- related differences in risks per Sv but does not distinguish on an individual basis.
- 16) *E* is in established use in medical practice for the comparison of doses from different techniques and the use of the same technique in different hospitals. It is also used to inform decisions on justification of patient diagnostic and interventional procedures, evaluation of cumulative exposures, and planning requirements in research studies.
- 17) *E* is also used in medical practice as a rough indicator of risk. Bearing in mind the uncertainties associated with risk projection to low doses, it is considered reasonable to use *E* as a rough indicator of possible risk, with the additional consideration of variation in risk with age, sex and population group. Adjustments for the body mass of individuals is discouraged as differences in dose and the associated inferred risk are small in comparison with uncertainties in risk projections.
- 18) The use of *E* as a rough indicator of risk is not a substitute for a risk analysis which would use best estimates of organ doses, appropriate information on the relative effectiveness of different radiation types, and age- sex- and population- specific risk factors, with consideration of uncertainties.
- 19) Collective effective dose is a valuable tool in the optimisation of protection, particularly for occupational exposures. However, its use to predict possible health effects should be treated with great caution and judged in relation to background incidence rates. Consideration of dose integration periods and dose bands should be considered, noting that levels of exposure may be difficult to estimate in public dose assessments.

1. INTRODUCTION

Effective dose was originally introduced in the 1977 Recommendations of the International Commission on Radiological Protection (ICRP, 1977) for the control of occupational and public exposures to external and internal sources of radiation. While the concept has remained essentially unchanged through the 1990 Recommendations (ICRP, 1991b) to the 2007 Recommendations (ICRP, 2007a), its use has been extended to members of the public of all ages, including *in utero* exposures of the embryo and fetus (ICRP, 2001, 2004a, 2006b). In addition, it is used in medical applications and a problematic and growing use of effective dose is in the assessment of medical exposures of patient populations of different ages, where the requirement is for a measure of risk to individuals (Martin, 2007a; Balonov and Shrimpton, 2012; Brenner, 2008, 2012; Harrison and Ortiz-Lopez, 2015).

The ICRP protection quantities – equivalent and effective dose (E) – enable the summation of doses from internal emitters and from external sources to provide a single number for comparison with dose limits, constraints and reference levels that relate to potential stochastic effects of whole body radiation exposure; that is, risks of developing cancer and of hereditary effects. Thus, the primary application of E is in the planning and demonstration of compliance in various situations of exposure of workers and members of the public. The calculation of E dose can be seen as a three-step process, starting with the calculation of absorbed dose to organs and tissues, in gray (Gy; joules per kg). Because radiation types differ in their ability to cause cancer per unit of absorbed dose, the second step is to multiply the calculated values of absorbed dose by radiation weighting factors that take account of the greater effectiveness of radiations including alpha particles and neutrons compared to beta particles and gamma rays. The results are termed equivalent dose, with the unit: sievert (Sv). The final step is to sum the equivalent doses to individual organs and tissues, multiplying each by a tissue weighting factor that represents its contribution to total detriment from uniform whole-body irradiation. The intention is that the overall risk should be comparable irrespective of the type and distribution of radiation exposure. E , in Sv, is the well-known quantity that is often referred to simply as dose.

It is important to recognise that while E is a risk-related construct for use in radiation protection, particularly in planning and optimising protection for workers and members of the public, it does not provide estimates of dose to individuals (ICRP, 2007a; Dietze and Menzel, 2004; Dietze *et al.* 2009). Absorbed doses to organs and tissues are calculated in mathematical phantoms and used to provide sex-averaged values of effective dose for a “reference person” (ICRP, 2007a, 2009a, 2010). Furthermore, the associated risks at low doses (< 100 mSv) are uncertain and the simplified risk-adjustments made using radiation and tissue weighting factors do not fully reflect our scientific understanding of radiation risks. For example, no account is taken of recognised differences between low energy mammography x-rays and cobalt-60 gamma rays (Hill, 2004). There is evidence that the relative effectiveness of different radiations is dependent on cancer type and there may, for example, be larger differences for liver cancer than for leukaemia (ICRP 2003b, Harrison and Muirhead, 2004). Tissue weighting factors are age- and sex- averaged values that conceal differences between cancer risk estimates for males and females, and at different ages, dependent on cancer type (ICRP, 2007a; NRC/NAS, 2006; Harrison and Day, 2008; UNSCEAR, 2013).

E and the tissue weighting factors used in its calculation relate to detriment from radiation induced cancer and hereditary effects. Detriment is calculated as defined by ICRP and

explained in detail in Annex A of *Publication 103* (ICRP, 2007a). The main source of data on cancer risks is the follow-up studies of the Japanese atomic bomb survivors (A bomb data), used to derive risk coefficients averaged over seven Western and Asian populations with different background cancer rates. The most recent ICRP (2007a) calculations of detriment use cancer incidence data, adjusted for lethality, loss of quality of life and years of life lost. In applying the risk factors obtained from epidemiological studies to exposures at lower doses and dose rates, ICRP applies a Dose and Dose Rate Effectiveness Factor (DDREF) of two for solid cancers and uses a linear-quadratic model for leukaemia. Weighting for hereditary effects is based on estimates of disease occurring in the first two generations. ICRP publishes nominal values of radiation detriment for an averaged world population, giving values for all ages (members of the public) and adults (workers).

The application of E in the control of stochastic effects for protection purposes relies on a number of key assumptions, principally that:

- a linear non-threshold (LNT) relationship between dose and risk applies at low doses
- acute and chronic exposures are equally effective at low doses
- external dose and internal dose from radionuclides deposited in body tissues can be summed, taking account of radiation quality through simple adjustments using radiation weighting factors.

Publication 103 provides detailed explanation of the purpose and use of the ICRP protection quantities in Chapter 3 and Annex B (ICRP, 2007a). However, further clarification and guidance have been sought, with identified issues including the following:

- 1) Confusion between equivalent dose (Sv) and effective dose (Sv) when they are not sufficiently carefully distinguished, particularly when considering doses from internal emitters that concentrate in specific organs eg iodine-131 (Gonzalez *et al.*, 2013).
- 2) The use of equivalent dose in setting limits for the avoidance of deterministic effects in the cases of irradiation the hands and feet, lens of the eye, and skin; that is, limits set below thresholds for the occurrence of acute damage to organs and tissues. In general, smaller differences are observed between radiation types in relation to deterministic effects than stochastic effects (ICRP, 2003b).
- 3) Confusion between operational quantities used to measure exposures to external sources and the protection quantities, and specifically between dose equivalent (the measured quantity for external radiation used as an estimate of effective dose) and equivalent dose (an intermediate quantity in the calculation of effective dose).
- 4) Apparent inconsistencies in the setting of radiation weighting factors, with a simple approach for all low LET radiations and alpha particles but greater complexity for neutrons, and the use of a different approach using quality factor in calculating operational quantities for neutron exposures.
- 5) The use of a single set of tissue weighting factors in the calculation of E for all age groups and both sexes, despite recognised age- and sex- related differences in cancer risks.
- 6) The calculation of E to a sex-averaged reference person, for children and adults, and the distinction between reference person and representative person.
- 7) The dose range over which E is applicable, particularly in considering higher doses that may occur in accidents that may involve high equivalent doses to individual organs / tissues (eg from iodine-131).
- 8) The apparent conservatism of calculating committed dose from internal emitters; that is, dose integrated over a 50 year period for adults and to age 70 years for other age

groups (ICRP 2007a). For long-lived radionuclides that have long biological retention times in body organs and tissues (eg. plutonium-239), dose is delivered over the whole time period such that only a small proportion is delivered within the year of intake. In contrast, for external sources, and for internally deposited radionuclides with short half-lives and/or short biological retention times, dose is delivered within the year of exposure/intake.

- 9) The calculation of E to the fetus following maternal exposures to internal emitters.
- 10) The suggestion that E dose should be calculated separately for males and females and for individuals of varying stature.
- 11) The use of E to estimate risks to individuals, particularly in evaluating exposure of patients undergoing medical procedures.
- 12) The use of collective effective dose to estimate risks to population groups.

The following section of this report reviews the scientific background to the use of the ICRP protection quantities, considering the key assumptions listed above that underpin their use. Subsequent sections focus on occupational, public and medical exposures and address the issues enumerated above.

2. BACKGROUND

2.1 Health risks

Publication 103 (ICRP, 2007a) provides detailed explanations of the judgments made and approaches taken to the quantification of radiation risks for radiological protection purposes. A distinction is made between two major classes of recognised health effects:

- ***Deterministic effects (harmful tissue reactions)*** occurring above dose thresholds for impairment of organ / tissue function, with severity increasing with increasing dose.
- ***Stochastic effects*** (cancer and heritable effects) assumed to occur with increasing probability with increasing dose, with no threshold below which there is no risk.

Deterministic effects

Publication 103 (ICRP, 2007a) made no changes to previously recommended dose limits for deterministic effects in relation to planned exposure situations, set in terms of equivalent dose, of 150 mSv/y for the lens of the eye and 500 mSv for skin and the hands and feet for occupational exposures, and 15 mSv for the lens of the eye and 50 mSv for skin for public exposures. However, there was accumulating evidence that the lens of the eye may be more sensitive to induction of opacities than indicated by earlier data (Worgul *et al.*, 2007; Neriishi *et al.*, 2007). *Publication 118* (ICRP, 2012a) provided an extensive and comprehensive review and analysis of tissue reactions caused by radiation that confirmed the judgements made in *Publication 103* (ICRP, 2007a; Annex A) regarding threshold doses in most cases, but more recent epidemiological data indicated a lower threshold for induction of cataracts of around 0.5 Gy compared with the values given in *Publication 103* (ICRP 2007a) of 2 Gy for acute exposures and 4 – 5 Gy for fractionated and protracted exposures. The available data suggested that acute and protracted exposures were similarly effective and were consistent with the assumption of a non-threshold relationship as well as a threshold of around 0.5 Gy (ICRP, 2012a; Bouffler *et al.*, 2016). In response to this evidence, ICRP (2012a) issued a Statement on Tissue Reactions recommending that the

equivalent dose limit for the lens of the eye for occupational exposures should be reduced to 20 mSv y⁻¹ averaged over 5 years, with dose in any year not exceeding 50 mSv.

The epidemiological studies on which judgement on cataract risk were based relate largely to external exposures to gamma rays (Ainsbury *et al.*, 2009; ICRP, 2012a) and in general there is limited information that allow comparisons of the deterministic effects of radiations of different qualities. However, available data indicate that differences between radiation types (eg alpha particles and neutrons cf. gamma rays) in their effectiveness per Gy in causing deterministic effects are smaller than differences in their effectiveness in relation to cancer induction. It can and has been argued, therefore, that use of equivalent dose limits to prevent deterministic effects is overly conservative and that specific lower radiation weighting factors should be applied. While it is important to recognise this conservatism, it is concluded that this is not of great practical concern in most cases and the complexity of introducing further quantities with different radiation weighting factors is not warranted. A distinction should be drawn here between reasonable conservatism as applied to the use of protection quantities to set limits for planned exposure situations and scientific judgements of the likelihood of observable effects in specific circumstances. For example, it would not be appropriate to use equivalent dose in the assessment of possible acute effects of an ingested alpha particle emitting radionuclide (eg. polonium-210).

A proposal worth consideration is that equivalent dose should not be used in this way to specify limits relating to deterministic effects, but that absorbed dose (Gy) would be the preferable quantity – this would draw a clear distinction between limits applying to deterministic effects, set in absorbed dose (Gy), and those applying to stochastic effects, set in effective dose (Sv). The limits for the lens of the eye, skin and hands and feet are relevant mainly to circumstances of exposure to penetrating low LET radiations, but to the extent that they will apply also to radiations of greater effectiveness per Gy (see below), their conservatism will compensate for any such differences. The proposal to discontinue the use of equivalent dose is widened to stochastic effects in section 2.2 below.

Publication 118 (ICRP, 2012a) proposed a threshold dose of 0.5 Gy for radiation-induced circulatory disease and the ICRP Statement on Tissue Reactions (ICRP, 2012a) drew attention to the need for medical practitioners to be aware since doses to patients of this magnitude could be reached during some complex interventional procedures. The meta-analysis of epidemiological data by Little *et al.* (2012) suggested that a linear non-threshold (LNT) dose-response relationship could be applied, resulting in risks at low doses of a similar magnitude to those inferred for cancer at low doses. Work is in progress to determine whether circulatory disease should be included as a component of low dose detriment but the current view is that different mechanisms of damage are likely to predominate at high and low doses and further mechanistic understanding is required to determine whether stochastic processes are involved in the development of radiation-induced circulatory disease (Hendry, 2015).

Stochastic effects

The main stochastic effect of radiation is cancer, with the principal source of information on risk being the epidemiological studies of the Japanese survivors of the atomic bombings at Hiroshima and Nagasaki, although with important information also coming from other studies (ICRP, 2007a). In general, the epidemiological data show a linear dose-response relationship between cancer rates and absorbed dose from gamma rays from around 100

mGy to a few Gy. Attempts are being made to extend observations to lower doses, notably studies on large worker cohorts (Muirhead *et al.*, 2003; Haylock *et al.*, 2016; Boice, 2015) and studies of children receiving CT scans (Pearce *et al.*, 2012; Mathews *et al.*, 2013; Huang *et al.*, 2014). The CT studies reported statistically significant elevation of cancer rates at doses of a few 10s of mSv. However, caution has been advised in the interpretation of these studies (Boice, 2015). A number of problems were identified including lack of information on the reasons for the scans and lack of individual dose reconstruction. It is considered that the patients may well have had underlying conditions that prompted their CT examinations, an example of so-called reverse causation (UNSCEAR, 2013; Walsh *et al.*, 2013, 2014). It will be important that future studies are rigorously controlled to avoid confounding.

A number of assumptions and judgements are made in quantifying low dose cancer risks (ICRP, 2007a). In applying the risk estimates derived from the A-bomb survivor data, a Dose and Dose Rate Effectiveness Factor (DDREF) of two is applied to solid cancers. Epidemiology provides no direct evidence of DDREF for solid cancer in humans but animal and *in vitro* data show curvilinear dose response relationships that support the use of a DDREF. For leukaemia, the A-bomb survivor data are consistent with the use of a linear-quadratic dose response relationship. Having obtained risk estimates for exposures at low doses of a few 10s of mGy, a linear non-threshold (LNT) dose-response relationship is assumed. It is the consensus view that this LNT dose-response assumption is the best interpretation of current mechanistic understanding of radiation-induced cancer at low doses for protection purposes (Preston, 2003, 2007; ICRP, 2007a; UNSCEAR, 2012b). Nevertheless, this assumption continues to be controversial with arguments for supra-linear low dose responses and for thresholds and/or hormetic effects.

The LNT dose-response assumption underpins the use of effective dose as a protection quantity, allowing the addition of external and internal doses of different magnitudes, with different temporal and spatial patterns of delivery. However, it should be recognised that while low doses may be measured or estimated with reasonable reliability, the associated cancer risk is uncertain, and increasingly uncertain as dose decreases.

Publication 103 (ICRP, 2007a) notes that there is no direct evidence from human epidemiological studies of heritable effects of radiation and justifies the inclusion of heritable risk in overall stochastic risks on the basis of observed mutational effects in experimented animals. Following a detailed analysis by ICRP (2007a) and UNSCEAR (2001), ICRP have applied estimates of heritable risk over two generations.

Nominal risk coefficients and Detriment

Annex A of *Publication 103* (ICRP, 2007a) provides a detailed explanation of the methodology applied to the calculation of nominal risk coefficients for radiation-induced cancer and associated values of detriment. Nominal risk coefficients are averaged across populations, all ages and both sexes to provide values that can be used as a basis for international protection standards. These risk coefficients are not intended for use in estimating risks to specific individuals. Detriment is a concept used to quantify the harmful effects of radiation at low doses, taking account of the severity of disease in terms of lethality and years of life lost. The following summary of the methodology used is closely based on that provided in Annex A of *Publication 103* as a description of the derivation of tissue weighting factors:

a) *Determine lifetime cancer incidence risk estimates for radiation-associated cancers:* For 14 organs or tissues, male and female lifetime excess cancer risks were estimated using both Excess Relative Risk (ERR) and Excess Absolute Risk (EAR) models, largely using analyses of follow-up data for the Japanese A bomb survivors.

b) *Apply a Dose and Dose-Rate Effectiveness Factor (DDREF):* The lifetime risk estimates were adjusted downward by a factor of two to account for a DDREF (except for leukaemia, where the linear-quadratic model for risk already accounts for the DDREF).

c) *Transfer risk estimates across populations:* To estimate radiation risk for each cancer site, a weighting of the ERR and EAR lifetime risk estimates was established that was considered to provide a reasonable basis for generalizing across populations with different baseline risks. (ERR:EAR weights of 0:100% were assigned for breast and bone marrow, 100:0% for thyroid and skin, 30:70% for lung, and 50:50% for all others).

d) *Nominal risk coefficients:* These weighted risk estimates, when applied to and averaged across seven western and Asian populations and between sexes, provided the nominal risk coefficients given in Table 1. The risk coefficients represent averages across selected Asian (Shanghai, Osaka, Hiroshima and Nagasaki) and Euro-American (Sweden, United Kingdom, US SEER) populations.

e) *Adjustment for lethality:* The lifetime risks for respective cancer sites, which were based on excess incident cancers, were converted to fatal cancer risks by multiplying by their lethality fractions, as derived from representative national cancer survival data.

f) *Adjustment for quality of life:* A further adjustment was applied to account for the morbidity and suffering associated with non-fatal cancers.

g) *Adjustment for years of life lost:* Since the age distributions of types of cancers differ, the average ages of the several types of cancer were estimated from national cancer data and converted to average years of life lost when a cancer occurs. An adjustment for years of life lost was then applied to the result of the previous steps.

h) *Radiation detriment:* The results of the calculations above yielded an estimate of the radiation detriment associated with each type of cancer. These, when normalized to sum to unity, constitute the relative radiation detriments in Table 1.

i) *Risks and detriment from heritable effects:* A detailed analysis of animal data led to the conclusion that risk should be defined for the first two generations rather than to equilibrium as done in Publication 60 (ICRP, 1991). Adjustments were then made to provide estimates of detriment, shown in Table 1.

Table 2 summarises the detriment adjusted risk coefficients derived in *Publication 103* (ICRP, 2007a) and compares them with the values used in *Publication 60* (ICRP, 1991b). The *Publication 103* values for cancer risks are based in considerably improved epidemiological analyses and use of incidence rather than mortality data. The lower values for heritable effects are considered a more scientifically defensible interpretation of the available experimental data – consideration of 5 -10 generations instead of two would not materially affect judgments on risk coefficients.

Table 1. Summary of *Publication 103* Nominal Cancer Risks and Detriment^a

a) Whole population

Tissue	Nominal Risk Coefficient (cases per 10,000 persons per Sv)	Lethality fraction	Nominal risk adjusted for lethality and quality of life*	Relative cancer free life lost	Detriment (relating to column 1)	Relative detriment ⁺
Oesophagus	15	0.93	15.1	0.87	13.1	0.023
Stomach	79	0.83	77.0	0.88	67.7	0.118
Colon	65	0.48	49.4	0.97	47.9	0.083
Liver	30	0.95	30.2	0.88	26.6	0.046
Lung	114	0.89	112.9	0.80	90.3	0.157
Bone surface	7	0.45	5.1	1.00	5.1	0.009
Skin	1000	0.002	4.0	1.00	4.0	0.139
Breast	112	0.29	61.9	1.29	79.8	0.017
Ovary	11	0.57	8.8	1.12	9.9	0.029
Bladder	43	0.29	23.5	0.71	16.7	0.022
Thyroid	33	0.07	9.8	1.29	12.7	0.015
Bone Marrow	42	0.67	37.7	1.63	61.5	0.107
Other Solid	144	0.49	110.2	1.03	113.5	0.198
Gonads (Hereditary)	20	0.80	19.3	1.32	25.4	0.044
Total	1715		565		574	1.000

b) Working age population (18-64 y)

Tissue	Nominal Risk Coefficient (cases per 10,000 persons per Sv)	Lethality fraction	Lethality-adjusted nominal risk* (relating to column 1)	Relative cancer free life lost	Detriment (relating to column 1)	Relative detriment ⁺
Oesophagus	16	0.93	16	0.91	14.2	0.034
Stomach	60	0.83	58	0.89	51.8	0.123
Colon	50	0.48	38	1.13	43.0	0.102
Liver	21	0.95	21	0.93	19.7	0.047
Lung	127	0.89	126	0.96	120.7	0.286
Bone surface	5	0.45	3	1.00	3.4	0.008
Skin	670	0.002	3	1.00	2.7	0.006
Breast	49	0.29	27	1.20	32.6	0.077
Ovary	7	0.57	6	1.16	6.6	0.016
Bladder	42	0.29	23	0.85	19.3	0.046
Thyroid	9	0.07	3	1.19	3.4	0.008
Bone Marrow	23	0.67	20	1.17	23.9	0.057
Other Solid	88	0.49	67	0.97	65.4	0.155
Gonads (Hereditary)	12	0.80	12	1.32	15.3	0.036
Total	1179		423		422	1.000

* Defined as $R \cdot q + R \cdot (1-q) \cdot ((1 - q_{\min}) \cdot q + q_{\min})$, where R is the nominal risk coefficient, q is the lethality, and $(1 - q_{\min}) \cdot q + q_{\min}$ is the weight given to non-fatal cancers. Here $q_{\min}$ is the minimum weight for nonfatal cancers. The $q_{\min}$ correction was not applied to skin cancer (see text).

+ The values given should not be taken to imply undue precision but are presented to 3 significant figures to facilitate the tracibility of the calculations made.

^a The values in the Table differ from these in the corresponding table in Annex A of the draft 2005 Recommendations as a consequence of an internal ICRP review of the calculations initially made.

Tissue weighting factors

Table 3 shows the tissue weighting factors, based on the relative detriment values shown in Table 1, as used in *Publication 103* (ICRP, 2007a) in the calculation of effective dose. As explained in Section 2.2, effective dose is calculated as the sum of equivalent doses to individual organs and tissues multiplied by their tissue weighting factors, thus making allowance for their contribution to total detriment. The intention of this procedure is that the overall risk per unit effective dose will approximate the values shown in Table 2, irrespective of the contributions made by doses to individual organs and tissues. Because of the uncertainties associated with the calculations of the nominal risk coefficients and detriment values shown in Table 1, and their application to low dose exposures to external and internal sources, the tissue weighting factor shown in Table 3 are simplified and rounded to avoid any impression of spurious accuracy. A single set of values is used for all ages and both sexes. The tissue weighting factor of 0.08 for gonads applies to detriment from cancer and heritable effects. A tissue weighting factor of 0.01 was applied to salivary gland and brain despite risks not being specifically quantifiable as it was judged that they are more sensitive to radiation-induced cancer than other tissues constituting the “remainder” group.

Table 2. Detriment-adjusted nominal risk coefficients (10^{-2} Sv^{-1})

Exposed population	Cancer		Heritable effects		Total	
	ICRP103	ICRP60	ICRP103	ICRP60	ICRP103	ICRP 60
Whole	5.5	6.0	0.2	1.3	5.7	7.3
Adult	4.1	4.8	0.1	0.8	4.2	5.6

Table 3. *Publication 103* tissue weighting factors

Tissue	w_T	$\sum w_T$
Bone-marrow, Colon, Lung, Stomach, Breast, Remainder Tissues*	0.12	0.72
Gonads	0.08	0.08
Bladder, Oesophagus, Liver, Thyroid	0.04	0.16
Bone surface, Brain, Salivary glands, Skin	0.01	0.04

*Remainder Tissues: Mean of doses to Adrenals, Extrathoracic (ET) region, Gall bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate (♂), Small intestine, Spleen, Thymus, Uterus/cervix (♀).

Age- and sex- specific cancer risks

The data provided in *Publication 103* (ICRP, 2007a) for the calculation of nominal risk coefficients, relative detriment and tissues weighting factors, for use in the calculation and application of effective dose, do not consider age and sex related differences in risk, except for the distinction between the whole population and the working age population (18 - 64 years). Risks for the working age population are somewhat smaller because risks are generally greater at younger ages. *Publication 103* does present, but does not use, separate risk factors for males and females, averaged over all ages, showing greater nominal risk coefficients and detriment values for females by a few 10s of percent.

Tables 4 and 5 show separate calculations for the ICRP (2007a) Euro-American and Asian composite populations, giving values of lifetime cancer risk as a function of age at exposure. Tables 6 and 7 present the same data as ratios to the values for the 30-39y Euro-American age-group. Comparison of these data shows that the same pattern is seen in both populations, with overall risks compared to those in the 30 – 39 year age-group being about double in the youngest age group (0 – 9 years) and about half by age 60 – 69 years. However, the data also show substantial differences between cancer types, with, for example, no age-dependence for lung cancer but substantial age-dependence for thyroid cancer, and some differences between the two populations in the age-dependence of risk for individual cancers. It should be recognised that the values given in Table 4 and 5 are the results of modelling, based on a set of assumptions (see above), all subject to uncertainties. While it is important to recognise the considerable uncertainties associated with low dose risk estimates, the overall conclusions regarding age-related changes in risk remain valid, with differences between individual cancers.

With regard to risks of *in utero* irradiation of the unborn child, *Publication 103* (ICRP, 2007a) refers to the review of *Publication 90* (ICRP, 2003a). The overall conclusion from the limited available data, is that it is reasonable to assume the overall risk of cancer from *in utero* irradiation is, at most, a few times that of the population as a whole and the *in utero* risk is judged to be no greater than that following exposures in early childhood.

For the operation of the protection system, it is of considerable utility to be able to set protection criteria that apply to all members of the public or all workers, and it is notable, therefore that the estimated differences in risk between males and females and between age groups are not large in comparison with the uncertainties associated with their estimation. The only distinction made between males and females for protection purposes is the treatment of occupationally exposed females during declared pregnancy when the fetus is regarded as a member of the public for the purposes of dose limitation (ICRP, 2007a). The calculation of doses to the fetus is considered in Section 2.2.

While nominal risk coefficients, detriment values and tissue weighting factors are calculated without allowance for age- and sex- related differences in risk within the public and worker populations, and dose limitation and optimisation of protection is applied without taking account of such differences, it is important for the purposes of this report to understand potential differences in risk to different population groups and individuals. Particularly in medical applications, there are situations in which clinicians require estimates of risk associated with particular procedures and better information may be required than that conveyed by nominal risk coefficients.

In addition to age- and sex- related differences in radiation risk, there are variations in radiation sensitivity between individuals related to genetic differences that are not generally well understood (ICRP, 2007a; AGIR, 2013; Bouffler, 2016). There are good prospects for increased understanding of such differences with advances in genetic typing and testing but with ethical challenges in the application of such information (Bouffler, 2016). However, current information is insufficient to quantify the effect of such differences in terms of individual risk.

Table 4. Lifetime risks of cancer incidence for the ICRP (2007a) Euro-American composite population (% per Gy)

Organ	Age at exposure (y)									
	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99
<i>Males</i>										
Lung	0.65	0.69	0.73	0.78	0.80	0.76	0.61	0.38	0.15	0.00
Stomach	0.93	0.73	0.57	0.43	0.31	0.20	0.12	0.06	0.02	0.00
Colon	1.49	1.22	0.98	0.79	0.60	0.43	0.25	0.12	0.03	0.00
RBM	1.06	1.05	0.77	0.76	0.78	0.65	0.49	0.33	0.17	0.03
Bladder	0.89	0.76	0.65	0.55	0.46	0.08	0.23	0.12	0.04	0.00
Liver	0.56	0.44	0.34	0.26	0.18	0.12	0.07	0.03	0.01	0.00
Thyroid	0.18	0.10	0.05	0.03	0.01	0.01	0.00	0.00	0.00	0.00
Oesophagus	0.12	0.11	0.11	0.11	0.12	0.14	0.15	0.15	0.10	0.00
Other	4.11	2.89	2.02	1.42	0.96	0.60	0.31	0.12	0.03	0.00
All cancers	9.98	8.00	6.22	5.12	4.22	3.00	2.23	1.32	0.55	0.04
<i>Females</i>										
Breast	4.92	3.34	2.21	1.44	0.84	0.45	0.21	0.08	0.02	0.00
Lung	1.36	1.46	1.58	1.70	1.78	1.72	1.39	0.82	0.29	0.01
Stomach	1.45	1.14	0.88	0.67	0.48	0.33	0.20	0.10	0.03	0.00
Colon	0.73	0.59	0.48	0.38	0.29	0.21	0.14	0.07	0.02	0.00
RBM	0.48	0.48	0.50	0.45	0.77	0.49	0.29	0.15	0.06	0.01
Bladder	0.70	0.61	0.52	0.45	0.39	0.17	0.24	0.14	0.05	0.00
Liver	0.24	0.19	0.15	0.11	0.08	0.06	0.03	0.02	0.00	0.00
Thyroid	0.92	0.52	0.26	0.13	0.06	0.02	0.01	0.00	0.00	0.00
Oesophagus	0.10	0.09	0.10	0.12	0.15	0.21	0.28	0.30	0.19	0.01
Ovary	0.51	0.40	0.31	0.24	0.17	0.11	0.06	0.02	0.01	0.00
Other	2.99	2.17	1.56	1.11	0.75	0.48	0.27	0.13	0.04	0.00
All cancers	14.39	10.99	8.54	6.78	5.76	4.26	3.10	1.83	0.70	0.02

Table 5. Lifetime risks of cancer incidence for the ICRP (2007a) Asian composite population (% per Gy)

Organ	Age at exposure (y)									
	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99
<i>Males</i>										
Lung	0.71	0.75	0.79	0.84	0.87	0.84	0.70	0.44	0.18	0.00
Stomach	1.56	1.26	1.02	0.79	0.59	0.40	0.23	0.10	0.03	0.00
Colon	1.77	1.44	1.18	0.92	0.70	0.47	0.26	0.12	0.04	0.00
RBM	1.06	1.06	0.78	0.76	0.79	0.67	0.52	0.34	0.18	0.02
Bladder	0.52	0.44	0.38	0.32	0.27	0.09	0.15	0.09	0.04	0.00
Liver	1.00	0.80	0.65	0.50	0.37	0.24	0.12	0.05	0.01	0.00
Thyroid	0.16	0.09	0.05	0.03	0.01	0.01	0.00	0.00	0.00	0.00
Oesophagus	0.22	0.19	0.18	0.17	0.17	0.18	0.18	0.16	0.10	0.00
Other	2.44	1.72	1.25	0.87	0.60	0.37	0.20	0.09	0.03	0.00
All cancers	9.43	7.75	6.27	5.20	4.37	3.26	2.37	1.39	0.60	0.02
<i>Females</i>										
Breast	5.22	3.49	2.37	1.50	0.91	0.47	0.22	0.08	0.02	0.00
Lung	1.32	1.41	1.50	1.59	1.64	1.61	1.39	0.91	0.40	0.01
Stomach	2.06	1.65	1.31	0.99	0.73	0.50	0.30	0.15	0.05	0.00
Colon	0.76	0.61	0.50	0.39	0.29	0.20	0.12	0.06	0.02	0.00
RBM	0.48	0.48	0.51	0.46	0.82	0.52	0.30	0.16	0.07	0.01
Bladder	0.49	0.43	0.38	0.33	0.29	0.18	0.19	0.13	0.06	0.00
Liver	0.49	0.39	0.32	0.26	0.20	0.15	0.09	0.04	0.01	0.00
Thyroid	1.23	0.68	0.38	0.19	0.09	0.03	0.01	0.00	0.00	0.00
Oesophagus	0.14	0.13	0.13	0.15	0.18	0.24	0.29	0.31	0.21	0.00
Ovary	0.38	0.29	0.22	0.16	0.11	0.07	0.04	0.02	0.01	0.00
Other	2.58	1.89	1.41	1.00	0.70	0.45	0.26	0.12	0.04	0.00
All cancers	15.16	11.45	9.03	7.01	5.98	4.42	3.22	1.98	0.88	0.02

Table 6. Ratios of lifetime risks for the ICRP (2007a) composite Euro-American population, relative to risks for the 30-39y age-group

Organ	Age at exposure (y)									
	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99
Lung	0.83	0.88	0.94	1.00	1.03	0.98	0.79	0.49	0.19	0.00
Stomach	2.14	1.69	1.32	1.00	0.71	0.47	0.27	0.13	0.04	0.00
Colon	1.90	1.55	1.25	1.00	0.76	0.54	0.32	0.16	0.04	0.00
RBM	1.40	1.39	1.02	1.00	1.03	0.87	0.65	0.44	0.23	0.04
Bladder	1.61	1.37	1.17	1.00	0.83	0.15	0.42	0.22	0.08	0.00
Liver	2.18	1.72	1.32	1.00	0.70	0.46	0.25	0.12	0.04	0.00
Thyroid	6.30	3.57	1.91	1.00	0.48	0.21	0.08	0.02	0.01	0.00
Oesophagus	1.13	1.02	0.97	1.00	1.10	1.24	1.38	1.37	0.88	0.03
Other	2.90	2.04	1.43	1.00	0.68	0.42	0.22	0.09	0.02	0.00
All cancers	1.95	1.56	1.22	1.00	0.82	0.59	0.44	0.26	0.11	0.01
<i>Females</i>										
Breast	3.43	2.33	1.54	1.00	0.59	0.32	0.14	0.06	0.01	0.00
Lung	0.80	0.86	0.93	1.00	1.05	1.01	0.82	0.48	0.17	0.00
Stomach	2.17	1.71	1.32	1.00	0.72	0.50	0.30	0.15	0.04	0.00
Colon	1.91	1.56	1.25	1.00	0.77	0.56	0.36	0.18	0.05	0.00
RBM	1.08	1.07	1.11	1.00	1.72	1.10	0.64	0.34	0.14	0.02
Bladder	1.55	1.34	1.16	1.00	0.85	0.37	0.52	0.32	0.12	0.00
Liver	2.11	1.67	1.30	1.00	0.73	0.51	0.31	0.15	0.04	0.00
Thyroid	7.29	4.08	2.07	1.00	0.44	0.18	0.07	0.02	0.00	0.00
Oesophagus	0.83	0.80	0.84	1.00	1.32	1.79	2.36	2.54	1.59	0.05
Ovary	2.16	1.71	1.32	1.00	0.70	0.44	0.24	0.10	0.03	0.00
Other	2.70	1.96	1.41	1.00	0.68	0.44	0.24	0.11	0.03	0.00
All cancers	2.12	1.62	1.26	1.00	0.85	0.63	0.46	0.27	0.10	0.00

Table 7. Ratios of lifetime risks for the ICRP (2007a) composite Asian population, relative to risks for the 30-39y age-group of the Euro-American composite population

Organ	Age at exposure (y)									
	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99
Lung	0.91	0.97	1.03	1.08	1.12	1.09	0.90	0.57	0.23	0.00
Stomach	3.60	2.90	2.35	1.82	1.36	0.92	0.53	0.24	0.08	0.00
Colon	2.25	1.83	1.50	1.18	0.89	0.60	0.34	0.15	0.05	0.00
RBM	1.40	1.40	1.03	1.01	1.05	0.89	0.68	0.45	0.24	0.02
Bladder	0.93	0.80	0.69	0.58	0.49	0.16	0.28	0.16	0.07	0.00
Liver	3.88	3.12	2.52	1.94	1.43	0.92	0.48	0.19	0.06	0.00
Thyroid	5.71	3.14	1.74	0.88	0.43	0.18	0.06	0.01	0.00	0.00
Oesophagus	1.98	1.74	1.59	1.53	1.55	1.60	1.62	1.48	0.88	0.01
Other	1.72	1.21	0.89	0.62	0.42	0.26	0.14	0.06	0.02	0.00
All cancers	1.84	1.51	1.23	1.02	0.85	0.64	0.46	0.27	0.12	0.00
Females										
Breast	3.63	2.43	1.65	1.05	0.63	0.33	0.15	0.06	0.02	0.00
Lung	0.78	0.83	0.88	0.93	0.97	0.95	0.82	0.54	0.24	0.00
Stomach	3.10	2.47	1.97	1.48	1.09	0.74	0.46	0.23	0.08	0.00
Colon	1.99	1.61	1.30	1.02	0.77	0.53	0.32	0.15	0.05	0.00
RBM	1.09	1.08	1.14	1.03	1.85	1.16	0.68	0.35	0.15	0.01
Bladder	1.09	0.95	0.84	0.74	0.65	0.40	0.43	0.28	0.12	0.00
Liver	4.36	3.53	2.89	2.29	1.80	1.31	0.78	0.35	0.11	0.00
Thyroid	9.75	5.39	2.98	1.48	0.68	0.27	0.09	0.02	0.00	0.00
Oesophagus	1.20	1.11	1.12	1.26	1.56	2.04	2.53	2.69	1.81	0.03
Ovary	1.62	1.23	0.94	0.69	0.48	0.30	0.17	0.08	0.02	0.00
Other	2.33	1.71	1.28	0.91	0.64	0.41	0.24	0.11	0.04	0.00
All cancers	2.24	1.69	1.33	1.03	0.88	0.65	0.48	0.29	0.13	0.00

Risks from internal emitters

The epidemiological data used as the basis for the derivation of nominal risk coefficients, detriment values and tissue weighting factors, as discussed above, relate almost entirely to external exposures to gamma rays, principally cancer incidence and mortality data for the Japanese A-bomb survivors. Although the values presented in Tables 1 and 2 (from *Publication 103*) are expressed as risk per Sv (equivalent dose), they are more correctly risks per unit mean absorbed dose (Gy) in the organs and tissues following uniform whole-body irradiation (Gy). Tables 4 and 5 give values of risk per Gy. However, the numerical values of absorbed dose and equivalent dose will be the same, as a radiation weighting factor of 1 is used for all low LET radiations, including gamma rays. An exception is the risk factor for bone cancer in Table 1 which was based on *Publication 60* (ICRP, 1991b) considerations of the risk of alpha particle irradiation from internally deposited radium-224. In this case, the risk per Gy was divided by an assumed value for the relative biological effectiveness (RBE)

of alpha particles compared with gamma rays of 20 to obtain an estimate of risk per Sv (or Gy low LET radiation). The radiation weighting factor used for alpha particles is 20 (see section 2.2).

An important question for the operation of the protection system is the extent to which risk factors derived principally from studies of short-term exposures to penetrating external radiation apply also to protracted irradiation from charged particles, with heterogeneity of exposure between and within organs and tissues. This question is particularly relevant to internal exposures to alpha particle emitting radionuclides, including radium-224, since alpha particles only travel very short distances (a few tens of microns) in tissue.

In relation to the application of external risk factors to internal exposure to alpha particle irradiation, a number of human studies (UNSCEAR, 2000, 2008; WHO, 2001) provide information that has been used to estimate risks of lung, liver, and bone cancer:

- Lung cancer – occupational exposure of uranium miners to radon-222 and daughters, with consistent data from studies of residential exposure.
- Liver cancer – patients given intravascular injections of ‘Thorotrast’, a colloidal thorium oxide preparation (^{232}Th is an alpha emitter), as a contrast medium for diagnostic radiology.
- Bone cancer – occupational exposure of radium dial painters to ^{226}Ra and ^{228}Ra ; patients given ^{224}Ra for medical conditions.

Harrison and Muirhead (2003) compared risk estimates for radiation-induced cancer derived for these exposures to alpha-emitting radionuclides and those derived for the atomic bomb survivors. They showed that, taking account of the greater effectiveness of alpha particles compared to gamma rays by up to a factor of around 20, the human data show consistency between estimates of radiation risk from internal emitters and external radiation. Similar conclusions were reached by Little *et al.* (2007) in an analysis of epidemiological data for internal emitters and comparison with A bomb survivor data. Support is also provided by animal and *in vitro* data comparing the effects of different radionuclides and external radiation (UNSCEAR, 2000, 2008; WHO, 2001). However, uncertainties in the dose estimates for internal emitters and in the risk factors should be recognised (Harrison and Muirhead, 2003; ICRP, 2007a; Harrison and Day, 2008).

In addition, an excess of leukaemia has been reported in Thorotrast-treated patients, and quantitative estimates of plutonium-239 induced lung cancer have been derived for Russian workers at the Mayak nuclear site (WHO, 2001; Harrison and Muirhead, 2003; Gilbert *et al.*, 2004, 2013). Comparison of leukaemia risks in Thorotrast patients and A bomb survivors suggested a low alpha particle RBE for this disease of around 1 – 2. Animal data provide some support for a low alpha particle RBE for leukaemia induction (Breckon and Cox, 1990; Ellender *et al.*, 2001; ICRP, 2003b). Marsh *et al.* (2014) undertook a detailed analysis of lung cancer risks per Gy from inhaled radon-222 progeny and plutonium-239, focussing on the results of a recent epidemiological study of French uranium miners (Rage *et al.*, 2012) and an epidemiological study of lung cancer in Mayak workers which applied the most recently published Mayak Worker Dosimetry System (MWDS-2008, Khokhryakov *et al.*, 2013). While the alpha particle dose from radon progeny is delivered predominantly in the airways with only a small proportion delivered to the alveolar regions, the opposite is the case for alpha particle decay of plutonium-239. Marsh *et al.* (2014) compared the published values of excess relative risk (ERR) from these studies and also calculated values of lifetime excess absolute risk (LEAR), comparing results with values based on the A bomb survivor data.

Both published values of ERR and calculated values of LEAR showed similar values for radon-222 progeny and plutonium-239 despite the very different dose distributions within the lungs, with central RBE values of around 10 – 20 in each case.

It can be concluded that the available epidemiological data, supported by animal data, indicate that it is reasonable for protection purposes to assume equivalence of risk per unit dose, once simple adjustment are made to account for RBE, between short duration exposures to external penetrating low LET gamma rays and protracted internal exposures to alpha particle emitting radionuclides, for which tissue doses will be substantially more heterogeneous.

2.2 Dosimetry

The procedure for the assessment of effective dose adopted by ICRP is to use *absorbed dose* as the fundamental physical quantity; to average it over specified organs and tissues; to apply suitably chosen radiation weighting factors to take account of differences in biological effectiveness of different radiations to give the quantity equivalent dose; and to consider differences in sensitivities of organs and tissues to stochastic health effects and their contribution to total detriment. Values of the equivalent dose to organs and tissues are weighted using tissue weighting factors that provide a simplified representation of relative detriment and the weighted equivalent doses are then summed to give the effective dose. This quantity is used to sum exposures to radiation from incorporated radionuclides and to external radiation fields. The description below is based on that provided in Chapter 4 and Annex B of *Publication 103* (ICRP, 2007a).

Absorbed dose

In radiation biology, clinical radiology, and radiological protection, the absorbed dose, D , is the basic physical dose quantity and is used for all types of ionising radiation and any irradiation geometry. It is defined as the quotient of mean energy, $d\bar{\epsilon}$, imparted by ionising radiation in a volume element and the mass, dm , of the matter in that volume, that is

The SI unit of absorbed dose is J kg^{-1} and its special name is gray (Gy). Absorbed dose is derived from the mean value of the stochastic quantity of energy imparted, ϵ , and does not reflect the random fluctuations of the interaction events in tissue. While it is defined at any point in matter, its value is obtained as an average over a mass element dm and hence over many atoms or molecules of matter. Absorbed dose is a measurable quantity and primary standards exist to determine its value. The definition of absorbed dose has the scientific rigour required for a basic physical quantity.

When using the quantity absorbed dose in practical applications, doses are averaged over tissue volumes. It is assumed that for low doses, the mean value of absorbed dose averaged over a specific organ or tissue can be correlated with radiation detriment for stochastic effects in that tissue with an accuracy sufficient for the purposes of radiological protection. The averaging of absorbed dose is carried out over the volume of a specified organ (e.g. liver)

or tissue (e.g. red bone marrow) or the sensitive region of a tissue (e.g. endosteal surfaces of the skeleton).

Equivalent dose and radiation weighting factors

The definitions of the protection quantities, equivalent and effective dose, are based on the average absorbed dose, $D_{T,R}$, due to radiation of type R in the volume of a specified organ or tissue T . The radiation R is given by the type and energy of radiation either incident on the body or emitted by radionuclides residing within it. The protection quantity *equivalent dose* in an organ or tissue, H_T , is then defined by

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

where w_R is the radiation weighting factor for radiation R . The sum is performed over all types of radiations involved. The unit of equivalent dose is J kg^{-1} and has the special name sievert (Sv).

In the early 1960s, radiation weighting in the definition of radiological protection quantities was related to the radiation quality as a function of LET and denoted as L in the $Q(L)$ function of *Publication 26* (ICRP, 1977). In *Publication 60* (ICRP, 1991b) the method of radiation weighting was changed, with the selection of a set of radiation weighting factors (w_R). The values of w_R were defined largely on the basis of the relative biological effectiveness (RBE) of the different radiations as determined in experimental studies. RBE values are generally measured in relation to common reference radiations: high energy x rays above about 200 kV or ^{60}Co or ^{137}Cs gamma radiation. Table 8 shows the w_R values adopted in *Publication 103* (ICRP, 2007a).

Table 8. *Publication 103* radiation weighting factors

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy (Fig.1)

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

Photons, electrons and muons are radiations with LET values of less than $10 \text{ keV}/\mu\text{m}$ that have always been given a radiation weighting of 1. However, the use of $w_R = 1$ does not imply that there are no differences in radiation quality of photons of different energies. This simple approach is considered sufficient for the intended applications of effective dose, e.g. for dose limitation, assessment and controlling of doses in the low dose range. In cases where individual retrospective risk assessments have to be made, more detailed information on the radiation field and appropriate RBE values may need to be considered if relevant data are

available. Heterogeneity of the radiation dose within cells, as can occur with Auger emitters incorporated into DNA, for example, may also require specific analysis.

The radiation weighting factor for neutrons reflects the relative biological effectiveness of neutrons following external exposure. The biological effectiveness of neutrons incident on the human body is strongly dependent on neutron energy (see *Publication 103*, Annex B). The energy function shown in Figure 1 takes account of the large contribution of secondary photons to the absorbed dose in the human body at lower energies, and the decrease of w_R at neutron energies above 100 MeV due to the increased contribution by protons.

Protons in cosmic radiation fields or fields near high-energy particle accelerators are mainly of very high-energy and it is considered appropriate to adopt a single w_R value for protons of all energies that is mainly based on radiobiological data for high-energy protons above 10 MeV. Pions are negatively or positively charged or neutral particles encountered in radiation fields resulting from interactions of the primary cosmic rays with nuclei at high altitudes in the atmosphere. These particles contribute to exposures in aircraft and are also found as part of the complex radiation fields behind shielding of high-energy particle accelerators.

Alpha particle exposures occur as a result of the inhalation or ingestion of alpha-emitting radionuclides. Information from experimental and epidemiological studies indicate that RBE values differ dependent on the organ and cancer type being considered. The distribution of

Fig. 1. Energy function for radiation weighting factor, w_R , for neutrons

radionuclides in organs and tissues and the estimation of dose is complex and associated with substantial uncertainties, resulting in a broad range of RBE values (see section 2.1; ICRP 2003, 2007). A single w_R value of 20 is used for alpha particle irradiation and the same value is used for fission fragments, and also as a conservative value for heavy ions.

It has been argued (eg. Thomas and Edwards, 2003) that the ICRP treatment of radiation weighting exhibits inconsistencies, is unnecessarily complex, and over-interprets the

available biological data (ICRP, 2003). For protection purposes, it is arguably sufficient to use two w_R values: 1 for low LET radiations and 10 for high LET radiations, including the high LET component of neutron dose. Such a scheme would not obviate the need for more complex calculations in situations that require the use of best available data to estimate dose and risk as accurately as possible – an example is the calculation of doses to astronauts which can be substantial and involve consideration of exposures to complex radiation fields (ICRP, 2013b). However, the current system of radiation weighting as specified in *Publication 103* (ICRP, 2007a) has the advantage of providing continuity of approach, and an important consideration is the relationship between effective dose and measurements made using operational quantities (see below).

Equivalent dose can be seen as an intermediate step in the calculation of effective dose. Exposure limits, constraints and reference levels in relation to stochastic health effects are set in terms of effective dose. Equivalent dose has been used to specify limits for the avoidance of deterministic effects, as discussed in Section 2.1, but these could more appropriately be set in terms of absorbed dose (Gy). Communication difficulties have arisen in situations where equivalent dose (Sv) and effective dose (Sv) have not been adequately distinguished, for example in explaining doses for intakes of iodine-131 for which the equivalent doses to the thyroid is more than twenty times the effective dose (Gonzalez *et al.*, 2013). There is also scope for confusion between equivalent doses and the operational quantity, dose equivalent (Sv). Such difficulties would be avoided if organ and tissue doses are referred to in terms of absorbed dose, if necessary specifying low and high LET components. For example, an intake of iodine-131 might result in an effective dose of 10 mSv, with a thyroid dose of 240 mGy (low LET). For ingestion of plutonium-239 by an adult member of the public, the committed effective dose is 2.5×10^{-7} Sv/Bq, dominated (>99.9%) by alpha particle radiation and contributions of 8.6×10^{-8} Gy/Bq to liver, 4.1×10^{-7} Gy/Bq to bone surfaces and 2.0×10^{-8} Gy/Bq to red bone marrow. It is proposed that the use of equivalent dose as a distinct protection quantity is discontinued.

Effective dose and tissue weighting factors

The effective dose, E , as introduced in *Publication 60* (ICRP, 1991b) and applied in *Publication 103* (ICRP, 2007a) is defined as:

$$\begin{aligned} E &= \sum_T w_T \sum_R w_R D_{T,R} \\ &= \sum_T w_T H_T \end{aligned}$$

where w_T is the tissue weighting factor for tissue, T and $\sum w_T = 1$. The sum is performed over all organs and tissues of the human body for which specific radiation detriment values can be calculated (Table 1) and tissue weighting factors can be specified (Table 3). As outlined above, the w_T values are chosen to represent the contributions of individual organs and tissues to overall radiation detriment from stochastic effects, averaged over all ages and both sexes. The w_T values are rounded and have only four different numerical values (Table 3), despite the greater differentiation possible on the basis of relative detriment (Table 1), to avoid the impression of unwarranted accuracy in relation to effects of low dose radiation.

The unit of effective dose is J kg^{-1} with the special name sievert (Sv). It is proposed that effective dose is retained as the sole protection quantity for the control of stochastic effects, used to set limits, constraints and reference levels and in the optimisation of protection. It

applies over the dose range of concern for the induction of stochastic effects and in this connection, questions have arisen regarding the upper limit to the applicability of effective dose. *Publication 103* (ICRP, 2007a) refers to setting of reference levels in relation to emergency planning in the range of 20 - 100 mSv effective dose. In principle, there is no reason why effective doses should not be used as a quantity at doses above 100 mSv: for example, as might be required as a short-term relaxation of worker doses in order to control an accident situation. However, two factors need to be taken into consideration at higher doses:

- 1) The potential for the occurrence of deterministic effects should be considered and avoided. For effective doses in the low 100s mSv where irradiation is reasonably uniform, severe deterministic effects (tissue reactions) would not be expected to occur, but if there was a significant contribution to the effective dose from radionuclides concentrated in particular organs (eg iodine-131 in the thyroid, inhaled insoluble radionuclides in the lung), tissue damage could occur. Notably, for ^{131}I , for example, an effective dose of 250 mSv could correspond to a thyroid dose of > 6 Gy.
- 2) A secondary consideration is that for doses in excess of 100 mSv (or more precisely doses to organs and tissues > 100 mGy) delivered at high dose rate, the DDREF of two applied in determining solid cancer risk at low doses will not apply, so that risks may be somewhat greater than might be assumed on the basis of *Publication 103* (ICRP, 2007) nominal risk coefficients.

Calculation of dose coefficients

For internal exposures, ICRP has published dose coefficients (Sv Bq^{-1}) for intakes of individual radionuclides by workers and members of the public, giving both equivalent doses to organs and tissues, and effective dose for adults and children (ICRP, 1979, 1980, 1981, 1987, 1989, 1993, 1994a,b, 1995a,b, 1996a, 1999, 2002a). Dose coefficients have also been provided for radiopharmaceutical doses to patients (ICRP, 1987, 1998b). For consideration in relation to occupational and environmental exposures, doses to the fetus following maternal intakes have been calculated and also doses to infants from radionuclides transferred to breast-milk (ICRP, 2001, 2004a). Details of the calculations are given in the relevant publications. In each case, biokinetic models are provided, used to describe the behaviour of radionuclides in the body and calculate energy deposition and absorbed dose in target organs (for which doses contribute to the calculation of effective dose) for transformations occurring in source organs (sites of radionuclide retention).

Publication 119 (ICRP, 2012b) provides a compilation of internal dose coefficients for workers and members of the public, calculated according to *Publication 60* methodology (ICRP, 1991b). It also includes conversion coefficients for occupational exposures to external radiation, abstracted from *Publication 74* (ICRP, 1996c), calculating the protection quantities from estimates of absorbed dose per unit air kerma or fluence, assuming whole-body irradiation by mono-energetic photons, electrons and neutrons in a number of idealised standard exposure geometries. *Publication 128* (ICRP, 2015) provides a compilation of dose coefficients for radiopharmaceuticals calculated using *Publication 60* (ICRP, 1991b) methodology.

Revisions of ICRP recommendations invariably require recalculation of dose coefficients because changes are made to the radiation and tissue weighting factors used in the calculation of equivalent and effective dose. In addition, improvements to the models used to calculate doses also lead to revised values. Work is currently in progress to provide replacement dose

coefficients based on the 2007 Recommendations (*Publication 103*), incorporating a number of important methodological improvements, including revised and updated biokinetic and dosimetric models. It should be noted, however, that while dose coefficients are revised following each new set of ICRP recommendations, these changes should be regarded as evolution and improvement as scientific knowledge improves rather than fundamental change, and there should be no requirement for the recalculation of previous dose assessments.

Computational phantoms (or mathematical models) of the human body are used to model energy deposition in organs and tissues from internal and external radiation exposures. These phantoms have generally been based on mathematical expressions representing geometric shapes that provide reasonable approximations to the shapes of body structures. This type of phantom was developed at the US Oak Ridge National Laboratory (Cristy, 1980; Cristy and Eckerman, 1987) for the Medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear Medicine. From the original adult MIRD phantom, several paediatric phantoms were developed to represent infants and children of various ages (Cristy, 1980). MIRD type models were developed by Stabin *et al.* (1995) for three stages of pregnancy. These models have been used in the calculation of ICRP dose coefficients.

More recently, a number of groups have developed so-called tomographic or voxel models based on medical imaging data, providing a more realistic representation of human anatomy. *Publication 110* (ICRP, 2009a), a joint report with ICRU, provided reference phantoms for the adult male and female derived in this way from imaging data for individuals. The individuals were chosen for their similarity to the external dimensions and organ masses of the reference adult male and female (ICRP, 2002a) and the models were subsequently adjusted for consistency with these data. The use of males and female phantoms rather than the hermaphrodite MIRD phantoms requires explicit sex-averaging in the calculation of effective dose. Thus, in future calculations, equivalent dose will be calculated separately for males and females and averaged in the calculation of effective dose to the sex-averaged reference person (Figure 2). Work is in progress to provide a set of reference phantoms for children of different ages and for the pregnant woman and fetus.

Publication 116 (ICRP, 2010) provided the first set of dose coefficients calculated using *Publication 103* (ICRP, 2007a) methodology and *Publication 110* (ICRP, 2009) anatomical models, considering occupational exposures to external radiation. The radiations considered are external beams of monoenergetic photons; electrons and positrons; neutrons; protons; pions (negative/positive); muons (negative/positive) and He ions. The organ dose conversion coefficients tabulated in the report represent ICRP/ICRU recommended values. Comparisons of the protection quantities, equivalent and effective dose, with corresponding operational quantities (see below) showed the latter to provide conservative estimates of dose in the majority of cases. Annexes and a CD provide detailed supporting information, including equivalent dose coefficients for the lens of the eye and skin.

Work is in progress to replace internal dose coefficients and provide associated bioassay data for occupational exposures and replace dose coefficients for members of the public and for radiopharmaceutical administrations to patients. ICRP has not previously provided dose coefficients for exposures of members of the public, including children, to external sources, but a joint report with ICRU is currently in preparation.

Fig. 2. Sex-averaging in the calculation of effective dose using *Publication 110* reference phantoms.

Calculation of skin doses

The first concern with regard to doses to skin is the avoidance of deterministic tissue damage. As discussed in section 2.1, the dose limits set to avoid such damage are equivalent doses of 500 mSv for workers and 50 mSv for members of the public. The standard approach to the calculation of skin doses is to determine the average dose to the most exposed 1 cm² at a depth of 70 µm (ICRP 1991a, 2007a). ICRP (1991a) refers to a range in epidermal thickness of from 20 µm to 100 µm for the majority of body sites but both ICRP and ICRU (1997) use a nominal average value of 70 µm for general dosimetric purposes. However, ICRP (2002a) has published reference values for the thickness of epidermis of 45 µm for the newborn child, and 1-year-old and 5-year-old children, 50 µm for 10-year-old children and 60 µm for 15-year-old children as well as 70 µm for adults. A legitimate question raised therefore, particularly in connection with environmental contamination with radioactive particles (eg. COMARE, 2014), is whether skin doses should be calculated at shallower depths for the younger age groups. Such considerations are important when calculating doses from radionuclides with low energy beta or alpha particle emissions. However, for a number of reasons, it appears most appropriate to continue to determine dose as an average over 1 cm² at a depth of 70 µm for all ages:

- Threshold doses and ED_{50} values (dose causing an effect in 50% of individuals) for skin damage are calculated in relation to a depth of 70 µm; different values are obtained for calculations relating to other assumed depths (Charles and Harrison, 2007; Harrison *et al.*, 2016). The cautious deterministic limit for workers of 500 mSv is calculated at 70 µm, as is the highly cautious value of 50 mSv for members of the public;

- The variations in skin thickness for different regions of the body substantially exceed the differences implied by the reference epidermal thickness values given in ICRP *Publication 89* (ICRP, 2002a);
- The ICRP Task Group on the biological basis for skin dose limitation considered that for normalising effects of different energy beta particle emissions from radioactive particles, the best measure was an average over 1 cm^2 at a depth of $150 \text{ }\mu\text{m}$ (ICRP, 1991a). A depth of $150 \text{ }\mu\text{m}$ corresponds approximately to the depth of the basal cell layer of the epidermis around hair follicles.

On the basis of these considerations, it is proposed that the most appropriate approach for general protection purposes is to continue to calculate dose averaged over 1 cm^2 at a depth of $70 \text{ }\mu\text{m}$ in all cases. However, in the evaluation of possible effects in individual cases, it may be appropriate to consider the effect of variations in skin thickness and uncertainties regarding locations of target cells.

In evaluating risks of stochastic effects, ICRP (1991b, 2007) relates the risk of skin cancer to the average doses to the total area of skin, 1.9 m^2 in adult man and, for example, 0.48 m^2 for a one year-old child (ICRP, 2002a). A number of animal studies, mainly involving skin exposures of mice and rats, have compared effects caused by radioactive particles irradiating small areas of skin with effects of spatially uniform radiation exposures. For the same average doses, there is little evidence of any dependence of cancer risk on spatial dose distribution (Charles *et al.*, 2003), supporting the ICRP approach of averaging dose in the assessment of cancer risks.

Operational quantities and dose assessments

For the monitoring of external exposures, operational dose equivalent quantities for area and individual monitoring have been defined by ICRU. Dose equivalent quantities are measurable and instruments for radiation monitoring are calibrated in terms of these quantities. In routine monitoring, the values of these dose quantities are taken as a sufficiently precise assessment of effective dose, and doses to the eye lens and skin. Dose assessment for intakes of radionuclides in occupational settings can be done by estimating intakes either from direct measurements (e.g. external monitoring of the whole body or of specific organs and tissues) or indirect measurements (e.g. urine, faeces or environmental samples) and using the same biokinetic models used to calculate dose coefficients.

For individual monitoring for occupational exposures to external radiation, the operational quantity is the personal dose equivalent, $H_p(d)$, which is the dose equivalent in ICRU (soft) tissue at an appropriate depth, d , below a specified point on the human body. The specified point is normally taken to be where the individual dosimeter is worn. For the assessment of effective dose from measurement of personal dose equivalent, a depth $d = 10 \text{ mm}$ and $H_p(10)$ has been chosen and if the dosimeter is worn on a position of the body that is representative of whole-body exposure, it is assumed that at low doses the value of $H_p(10)$ provides an effective dose value that is sufficiently precise for protection purposes. For the assessment of the dose to the skin and to the extremities, the personal dose equivalent, $H_p(0.07)$, with a depth $d = 0.07 \text{ mm}$, is recommended for use as an operational quantity. For the case of monitoring the dose to the lens of the eye, a depth $d = 3 \text{ mm}$ has been proposed. Although *Publication 103* (ICRP, 2007a) considered that measurement of $H_p(3)$ may be unnecessary, the increased importance of the lens of the eye with the reduction in the dose limit to 20 mSv

per year (ICRP, 2012) has led to a re-evaluation of its application (ICRP, 2010). In some situations in which individual monitoring is not carried out (e. g. exposure of air crew), an assessment of effective dose may be performed by area monitoring applying the quantity ambient dose equivalent, $H^*(10)$, and calculating effective dose using the appropriate conversion coefficients.

Effective doses for medical exposures are calculated using dose coefficients that relate measurable quantities to the protection quantities. These measurable quantities for radiography and fluoroscopy include entrance surface air kerma (ESAK, K_e), which is a measure of the dose to the skin surface relative to air, and kerma-area product (KAP, P_{KA}), which is the product of the air kerma incident on the patient and the area of the X-ray beam at the skin surface and provides a measure of radiation entering the patient (Jones and Wall, 1985; Hart *et al.*, 1994, Ranniko *et al.*, 1997, Kramer *et al.*, 2004). For computed tomography (CT) examinations, the dose quantity is the dose-length product (DLP, P_{DL}) which is the dose within individual slices of the scan multiplied by the scan length (IMPACT, CTExpo, Wall *et al.*, 2011, Lee *et al.*, 2012]. For nuclear medicine procedures the amounts of radioactivity in radiopharmaceuticals administered to patients is used [ICRP 1987, 1998b, 2008; Stabin, 1996; Stabin *et al.*, 2005]. More comprehensive scientific descriptions of these quantities are included in the glossary. Tabulated conversion factors are available in the above references, to allow effective doses for a reference adult or reference paediatric patients of ages 0 y, 1 y, 5 y, 10 y and 15 y to be calculated from the measured quantities for a wide range of procedures. Such assessments give an indication of the radiation doses to patients that are sufficient for most requirements.

Radionuclides incorporated into the human body irradiate tissues over time periods determined by their physical half-life and their biological retention within the body. Radionuclides used in radiopharmaceutical preparations invariably have short half-lives but general occupational and public exposures can include radionuclides with long physical half-lives and biological half-times and may give rise to doses to body tissues for many months or years after the intake. The need to regulate exposures to radionuclides and the accumulation of radiation dose over extended periods of time has led to the definition of committed dose quantities. The committed dose from an incorporated radionuclide is the total dose expected to be delivered within a specified time period. The committed equivalent dose, $H_T(\tau)$, in a tissue or organ T is defined by:

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_T(t) dt$$

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

$$E(\tau) = \sum_T w_T H_T(\tau)$$

For compliance with dose limits, the Commission continues to recommend that the committed dose is assigned to the year in which the intake occurred. For workers, the committed dose is normally 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 of radionuclides 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. For infants and children the dose is evaluated to age 70 years.

It has been argued that the use of committed dose introduces hidden conservatism into calculations of doses from annual intakes (Gonzalez *et al.*, 2013). For some radionuclides, with long half-lives and long biological retention times, only a small proportion of the committed dose is delivered in the year of intake. For plutonium-239, for example, effective dose in the first year after intake will be generally less than 10% of the total committed dose. For most radionuclides, however, this effect will be much less significant and for many, including iodine-131 and caesium-137, dose will be delivered entirely or very largely in the year of intake. For practical purposes, the use of committed dose ensures that longer term exposures from intakes of radionuclides are taken into account.

Collective dose

For the purpose of optimisation of radiological protection, the Commission has introduced the collective dose quantities (ICRP, 1977, 1991b). These quantities take account of the group of persons exposed to radiation and the period of exposure. They are obtained as the sum of all individual doses from a source over a specified time period. 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, 1991b). The special name used for the collective dose quantity is the ‘man sievert’. Since the intention of the collective dose is to serve as an instrument in the optimisation of radiological protection only the collective effective dose is retained in the present system.

The use of collective effective dose relies on the validity of the application of the LNT dose-response relationship, and the additivity of different types of radiation exposure. Collective dose is mainly an instrument for optimisation, for comparing radiological technologies and protection procedures. It is used, for example, by UNSCEAR (2008, 2010) to compare doses from different sources of radiation. Collective dose is not intended as a tool for epidemiological risk assessment and it is therefore inappropriate to use it in formal risk projections for such studies. However, while not intended for this purpose, an estimation of collective effective dose, or collective dose to a specific organ or tissue, may serve as an indication of possible health risks and so help determine whether an epidemiological study has the prospect of providing meaningful results. Also, in the event of a major nuclear release, an early estimate of collective dose can be useful in assessing the possible extent of any health effects and this help support emergency response decisions. Any estimates of collective dose and related health risks determined for such purposes should be treated with caution and the results put into context; for example, by comparison with the normal incidence of the health consequence. In particular, the computation of cancer deaths based on collective doses involving trivial exposures to large populations is not reasonable and should be avoided.

To avoid aggregation of, e.g., very low individual doses over extended time periods and wide geographical regions, ideally limiting conditions need to be set. Where possible, the dose range and 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:

$$\sum_{E_1 \leq E < E_2} \frac{dN}{dE} dE \Delta T$$

where dN/dE denoted the number of individuals who are exposed to an effective dose between E and $E + dE$ and ΔT specifies the time period within which the effective doses are summed. As discussed in the following section on occupational and public exposures, there

are some practical difficulties in carrying out such summations of individual doses for members of the public but a breakdown of collective doses for different time periods and population groups is possible.

2.3 Uncertainties

ICRP dose coefficients are provided as reference values for planning, optimisation of protection and the determination of compliance, and are used for this purpose around the world. While the models used to calculate absorbed doses can be regarded as making best use of available scientific knowledge, they are subject to uncertainties due to the availability of data for their construction. In general, uncertainties for assessments of radiation doses from internal exposures, including the biokinetics of radionuclides and radiopharmaceuticals, are larger than those from external exposures. The degree of uncertainty differs between various radionuclides and radiopharmaceuticals. While the operation of the protection system does not depend on knowledge of such uncertainties, it can be informative to understand the reliability of dose estimates.

By design, radiation and tissue weighting factors used in the calculation of effective dose are not best scientific estimates but simplified risk-related adjustments. Effective dose is not a scientific quantity, is not amenable to explicit consideration of uncertainties, and such considerations would not help its application and use within the protection system. In circumstances in which best estimates of dose and risk are required, absorbed dose to organs and tissues would be used, together with RBE data and appropriate age and sex specific risk factors, and in such cases, consideration of uncertainties would be important if not essential.

In practice, there are clearly uncertainties in all stages of the determination of radiation exposures, calculation of doses and any interpretation in terms of associated risk. Operational quantities used to measure radiation exposures in occupational and medical practice are subject to relatively small uncertainties. Greater uncertainties apply to the determination of exposures of members of the public where direct measurements are not usually either practical or possible.

For both external and internal radiation exposures, anthropomorphic dosimetric models enable the calculation of organ doses to reference individuals of different ages for standardised exposure conditions with good reliability, considering either external radiation incident on the body or internal exposures from source to target organs. Uncertainties are greatest for radiations of low penetration, particularly alpha particles and low energy beta particles, for which the location of target cells in particular tissues may be important (eg. in skeletal tissues and the alimentary and respiratory tracts). For internally deposited radionuclides and radiopharmaceuticals, the additional uncertainty associated with the biokinetic modelling of their organ retention and excretion differs according to the quality of the human and animal data used to define model parameters and reference values. A distinction should be drawn between uncertainties in mean organ doses and effective dose estimated for a reference person and variability between individuals in an exposed group or population or between medical examinations. For example, most medical procedures involve exposure of a limited number of tissues within the body and while uncertainties will be small for standardised exposure assumptions, there may be substantial variation in organ doses between individual examinations. For example, for radiology examinations, values for the mean absorbed doses to organs and tissues on the periphery of an x-ray field, for which only

a portion will be exposed, are dependent on collimation of the x-ray field, and will tend to be more variable than absorbed doses to organs that lie fully within the primary beam. For example in chest radiographs, the proportion of the liver included can vary substantially depending on the lower boundary of the field and the thyroid can sometimes be exposed to the primary beam, while the length and position of the scanned region of a CT scan will determine the organs irradiated. Variations in effective dose when scan boundaries are changed are often less significant than those in organ and tissue absorbed doses, because E is calculated from measured dose quantities, such as KAP and DLP, that relate to the whole examination (section 2.2), and because increases in dose to particular organs/tissues are often compensated by decreases in doses to other organs/tissues. Another example regarding dose variability relates to the effect of automatic modulation of tube current according to patient attenuation in CT examinations of the thorax. Sookpeng *et al.* (2015) showed that doses to individual organs per DLP differed by factors of 30-40% from those in scans when no modulation was used, while the effective doses varied by $\pm 10\%$.

In many cases, data obtained from computer simulations for exposure of anthropomorphic phantoms are quoted to great accuracy to minimize rounding errors in calculations with, for example, four significant figures. This has led some users, particularly in medical applications, to quote effective dose to more than two significant figures, implying an accuracy that cannot be justified because of the approximations and uncertainties in the calculations. Effective dose should, therefore, be quoted to no more than two significant figures and when the effective dose is less than 1 mSv, one significant figure is appropriate.

In general, uncertainties in measurements and calculations of low dose exposures will be substantially less than uncertainties in associated risk of stochastic health effects. As discussed in the Introduction and Section 2.1, risk estimation at low doses depends on the LNT dose-response function and the assumed equivalence of acute and chronic exposures from external and internal sources. While low doses may in many cases be measured or estimated with reasonable reliability, the associated cancer risk is uncertain, and increasingly uncertain as dose decreases.

3. OCCUPATIONAL AND PUBLIC EXPOSURES

The use of effective dose is well established for controlling and monitoring occupational and public exposures. It provides a robust approach to enable external and internal exposures from a variety of different sources and types of radiation to be summed and compared with appropriate limits, constraints and reference levels. These limits, constraints and reference levels are set for all workers and all members of the public, recognising differences in risk between individuals and population groups, and also recognising that exposures may continue over a whole or working lifetime. The following sections consider the use of effective dose for occupational and public exposures, covering planned, existing and emergency exposure situations, considering individual and collective doses.

3.1 Occupational Exposures

Effective dose is an important tool for the management of all types of exposure situation. In planned exposures, it is used in prospective assessments for optimization of radiological protection and to ensure that operations will be carried out within the relevant limits and constraints. The sum of prospective external and internal exposures is used in such assessments to consider both individual and collective exposures. The collective effective dose is a useful tool for operational radiation protection, notably when planning complex work involving multiple workers where it is important to consider the total exposures as well as the exposure to the individual workers. Prospective assessments are based on estimations of the likely exposures from particular types of work and take into account experience in similar situations elsewhere. Collective and individual effective dose estimates can then be used to optimise protection, ensuring that the reductions in exposures for some workers are balanced against the potential increase in the number of workers exposed to smaller doses.

Retrospective assessments of effective dose for occupational exposures are used for demonstrating compliance with regulatory requirements, documentation of exposures for regulatory purposes (e.g. workers' dose records) and demonstrating that the system of protection has been adequately implemented. The effective dose is calculated for both external and internal irradiation and will often be based on specific measurements, for example, from a personal dosimeter or of radionuclides in urine. However, it is important to note that although effective dose is estimated for a specific individual, it remains a formal protective quantity in the system of radiological protection. It is defined for the reference person with a fixed set of anatomical and biokinetic parameters for the human body (ICRP, 2007a). The definition of effective dose precludes any type of individualization (e.g. taking into account body size or sex) and, as noted earlier, dose limits, constraints and reference levels were set to apply to all workers. Therefore, a value of effective dose given for an occupationally exposed person is generalized with respect to the human body properties, but may, however, be more specific with respect to the exposure conditions (see below).

For external irradiation, while effective dose is the primary quantity that should be evaluated, it may also be necessary to explicitly evaluate annual doses to the lens of the eye, the skin and to the hands and feet. The specific occupational dose limits for these organs and tissues (Section 2) may be limiting depending on the particular situation, notably for non-uniform irradiation or where there is a significant beta dose component resulting in irradiation of the skin and/or lens of the eye. Occupational doses from external exposures are normally determined by individual monitoring using personal dosimeters worn on the body. The main operational quantities for individual monitoring are $H_p(10)$, $H_p(3)$ and $H_p(0.07)$, as discussed in Section 2, and personal dosimeters can be set to measure all of these quantities. Provided that the personal dosimeter is worn in a position on the body that is shown to be representative of whole-body uniform exposure, $H_p(10)$ provides a sufficiently precise estimate of effective dose for protection purposes. Similarly, $H_p(0.07)$ can be used as a sufficiently precise assessment of skin dose in moist circumstances and $H_p(3)$ provides a better measure of eye dose. In situations where the dose to the body is known to be non-uniform, dosimeters may be worn in positions to determine doses to the most exposed organs, such as the eye lens. Where appropriate, adjustment factors may be used to provide approximate evaluations indicative of likely levels of effective doses. For example, lead / rubber protective aprons worn in radiology departments to protect sensitive organs within the trunk leave the head and neck unshielded. A single unprotected dosimeter worn at the collar of the apron can give indicative dose levels for both the eye and body, from which an assessment can be made of whether any additional monitoring is required. More specific information may be required on dose to the eye lens, or dose to the protected tissues to enable a more realistic value to be determined for effective dose. In the rare cases of a significant

contribution to external exposure of weakly-penetrating radiation, the contribution of the skin dose to effective dose also needs to be considered.

For internal exposures, committed effective doses are determined retrospectively based on the results of individual monitoring or, in exceptional circumstances, monitoring of radionuclide concentrations in air or other media such as surface contamination. Information may be obtained by individual monitoring of radiation emitted from the whole body using a whole body counter or from specific organs and tissues using other external counting devices, and by measurements of excretion in urine and faeces. These measurements are interpreted using the biokinetic models used in the calculation of dose coefficients to provide estimates of intake by inhalation or ingestion (or both). Dose coefficient then give values of effective dose for the estimated intakes. Calculations are done using reference biokinetic models and reference dose coefficients as published by ICRP. If sufficient information is available and assessed doses warrant a detailed assessment, changes can be made to the assumed particle size distribution of an inhaled material and its solubility and absorption characteristics in the respiratory and alimentary tracts. Since such changes relate to exposure conditions in the workplace, it is appropriate to apply them in the estimation of intake and the calculation of effective dose. Examples of the use of material specific data in the calculation of doses from inhaled radionuclides have been given by ICRP (2002b).

ICRP has stated that changes should not be made in biokinetic assumptions that relate to individuals in the calculation of effective dose (ICRP, 2007a). However, internal radiation doses may be based on a series of measurements of radionuclides in urine for a particular individual. The standard models used to estimate effective doses may not give a particularly good fit to the observed excretion data and it may be possible to obtain a better fit by changing the reference model parameters. The resulting estimated doses should be clearly distinguished from the standard calculation of 'effective dose' and if it is agreed that such dose information should be added in the individual's dose record, this difference should be clearly noted.

In specific circumstances it may be necessary to consider the incorporation of radionuclides through the skin or wounds for occupational exposures. However, this should not be a normal consideration for planned exposure situations where the situation is controlled; for example, protective clothing might be worn and any wounds or abrasions would be covered. The possible intake of radionuclides via wounds may need to be considered as part of any assessment of potential exposures where unplanned events lead to such intakes.

Existing exposure situations are those that are already in existence when a decision on control has to be made. They include situations involving exposures from naturally occurring radionuclides in the workplace and from man-made radionuclides, such as land contaminated by previous nuclear site operations. In addition the management of long-term contamination resulting from an emergency situation should also be treated as an existing exposure situation. The treatment of occupational exposures due to radon isotopes, primarily radon-222, and their decay products is addressed in *Publication 126* (ICRP, 2014). A report on the use of naturally occurring radioactive materials (NORM) in various industries is in preparation. For existing exposure situations, the use of effective dose is a firm basis for decisions on whether control measures are required and whether the exposure should be treated as occupational. Similar considerations apply to those addressed above for planned exposures.

Emergency exposure situations may arise in the workplace during the operation of a planned exposure situation and any other unexpected situation might result in the emergency exposure

of workers. There are two situations of relevance for emergency exposure situations. Firstly, if there is an accident or failure in control in the workplace, workers may be exposed to higher than normal radiation exposures. It is important to quickly assess what such exposures might have been in order to determine if medical intervention is required. Effective dose has a role in providing an initial indication of whether exposures are such that deterministic effects could be observed or if additional steps need to be taken to control any further exposures. At a later stage, a full retrospective risk assessment may be required following over-exposures in which effective dose will have a limited role; risk to individuals should be evaluated in such circumstances using best estimates of organ doses, appropriate RBE data and age-, sex- and population- specific risk factors (Section 2).

The second situation is in the immediate aftermath of an accidental release or in an on-going emergency where emergency exposures for workers may be required to bring the situation under control or to introduce protective measures to safeguard others. In these situations it may be possible to plan the exposures to some extent and it is appropriate to use effective dose as part of this process. However, it may also be important to take into account exposures of the skin, if there could be contamination particularly of low energy emitters, or of other organs if there are significant intakes by inhalation (ideally the use of personal protective equipment should minimise internal exposures in such circumstances). As discussed in Section 2, there is no reason in principle why effective dose should not be used as a protection quantity at doses in the low 100s mSv, for example, as might be required as a short-term relaxation of worker doses in order to control an accident. However, caution would be required in such circumstances to avoid deterministic effects, particularly when considering doses from radionuclides that concentrate in particular organs.

The presence of wounds, abrasions, burns or other pathological damage to the skin may greatly increase the ability of radioactive materials to reach subcutaneous tissues and thence the blood and systemic circulation. Although much of the material deposited at a wound site may be retained at the site, and can be surgically excised, soluble (transportable) material can be transferred to the blood and hence to other parts of the body. These events occur only as a result of accidents, each event will, therefore, be unique and need to be assessed by occupational health physicists and medical staff. ICRP has not given advice on the interpretation of wound monitoring data. The biokinetic models that have been developed for various radionuclides are, however, applicable to the soluble component of any deposit in cuts or wounds that enters the blood circulation. To provide a means for calculating doses resulting from radionuclide-contaminated wounds, the National Council on Radiation Protection and Measurements, in collaboration with the ICRP, has developed a biokinetic and dosimetric model for such exposures (NCRP, 2007). The dose coefficients and data given by ICRP could therefore be used in conjunction with the NCRP wound model parameter values to obtain estimates of organ doses and effective dose for radionuclides that have entered the blood from the wound site.

3.2 Public Exposures

Planned exposures to external and internal sources occur in a range of situations, including the following:

- visits to controlled or supervised areas

- access to areas accessible to members of the public adjacent to controlled areas,
- discharges of radioactive material to the environment,
- environmental releases following disposal of radioactive waste,
- handling of consumer products containing radioactive material.

Both prospective and retrospective assessments are carried out for planned exposure situations. Prospective assessments are carried out for optimisation purposes, ensuring that effective doses to the representative person are below the relevant dose constraint for the public; such assessments are necessarily carried out using modelling. Retrospective assessments may be carried out to demonstrate compliance with dose limits and constraints. Ideally such assessments would be based on monitoring of people and the environment but this is not always possible as the levels are too small to be detected. The uncertainties associated with assessments should be recognised. Collective effective doses may also be estimated as an input to the optimisation process or for comparative purposes as discussed below.

Existing exposure situations arise from:

- contamination of areas by residual radioactive material originating from past nuclear operations, radiation emergencies or past activities that were subject to regulatory control but not in accordance with current requirements,
- use of commodities, including food, feed, drinking water and construction materials, that incorporate natural or residual man-made radioactive material,
- exposure to natural sources, including radon indoors.

For existing exposure situations, prospective assessments are carried out to determine the annual effective dose to the hypothetical person as an input to optimisation studies and to ensure compliance with the relevant reference level of dose established for the situation of interest. Existing exposure situations can continue for many years and radiation conditions may change slowly enabling past monitoring data to be used to estimate future effective doses. Measurements of people and the environment can be used, if available, for retrospective assessments of annual effective dose to demonstrate compliance with the relevant reference level of effective dose.

Emergency exposure situations may occur during the operation of a planned exposure situation, from a malicious act or from any other unexpected situation, and will require urgent action in order to avoid or reduce radiation doses. Members of the public may be subject to external or internal exposure through various pathways from radionuclides dispersed in natural or inhabited environments. Prospective assessments may be carried out as part of emergency planning for possible future accidents or in relation to an accident that has occurred to determine what actions are required. Effective doses are estimated as input to the optimisation process and for comparison with relevant reference levels. Depending on the nature of the release, it might also be important to consider estimates of dose to specific organs or tissues; e.g. for accidents involving releases of iodine-131, it is important to specifically consider doses to the thyroid. Emergency exposures are usually of short duration and it is important to take account of differences in dose as a function of age at exposure. Consideration of exposures of pregnant and breast-feeding women may also be important. Retrospective assessments of effective dose due to emergency exposures may be required to determine any necessity for medical follow-up. In such cases, individual monitoring data (external and internal exposures) and/or biological dosimetry measurements would be required as well as measurements of radionuclides in various environmental media. It is

important to recognise uncertainties associated with the assessment of doses for emergency exposure situations, including those associated with measurements of people and the environment as well as in modelling results. Measurements may have been carried out for public reassurance purposes and so have relatively high limits of detection and significant uncertainties in conversion to dose. Retrospective assessments can also be used to refine the prospective dose assessments to reduce uncertainties and to improve the optimisation process.

Effective dose is the key quantity used for the purposes of radiation protection of the public (ICRP, 2007a). The annual effective dose to members of the public is the sum of the effective dose obtained within the year from external exposure and the committed effective dose from the intake of radionuclides during the year. External exposures may occur from proximity to controlled areas where sources of external radiation are used in industry, hospitals, research establishments and nuclear plants. External exposures of individuals may also occur from radionuclides released from installations and which are present in the air, soil, or water. Internal exposures can occur by inhalation of radionuclides in the air or by ingestion of radionuclides in food or water.

For protection purposes, i.e. for optimization of radiation protection and for comparison with dose constraints or limits or reference levels, effective dose is usually assessed for a real or, more frequently, hypothetical person receiving a dose that is representative of the more highly exposed individuals in the population (the right tail of a distribution of individual doses within a particular cohort) termed the ‘representative person’. The concept of the ‘representative person’ was introduced in *Publication 101* (ICRP, 2006b) to replace the less quantitatively defined concept of the ‘critical group’. A number of possible cohorts containing people of various ages with different occupations, habits and food consumption rates would generally be considered to define the representative person. One approach is to estimate the average dose in the upper 10% percentile of the distribution of individual doses within a cohort.

In the dose assessment process, a number of reference persons of different age and sex can be considered, as specified in *Publication 89* (ICRP, 2002a). The full set of six age-groups are the 3 month-old infants, 1y, 5y, 10y, and 15y old children and adults. In addition, ICRP considers doses to the embryo/fetus and to the breast-fed infant following intakes of radionuclides by the mother. In *Publication 103* (ICRP, 2007a), it is noted that in most cases the dose to the embryo/fetus and breast-fed infant will be small compared to doses received by the adult. However, this is not always the case and for four radionuclides, phosphorus -32 and -33, calcium-45 and strontium-89, the fetus / breast-fed infant may receive significantly higher doses than other age groups in some exposure situations and therefore may be designated as the representative person. Although doses in a year are required for comparison with dose criteria, it may be adequate to carry out a simplified dose assessment using an annual intake of radionuclides by the mother and applying the dose coefficient for chronic exposure of the fetus throughout pregnancy. If a more detailed assessment is required, the annual intake by the mother should be assumed to occur over the nine months of pregnancy and three months of breastfeeding. *Publication 101* (ICRP, 2006b) concludes that consideration of three age groups, 1y and 10 y old children and adults, is sufficient for most dose assessments, especially for long-term exposures when individual cohort members will naturally proceed through age groups.

As discussed in Section 2, concern has been expressed regarding the use of a single set of tissue weighting factors in the calculation of effective dose, applied to all age groups

including the embryo/fetus and infant. The weighting factors are used to allow for the contribution of individual organs and tissues to total detriment for stochastic effects while not over-interpreting knowledge of risks of low dose radiation exposure. They do not represent scientific best judgements for any specific age group. Application to the embryo/fetus is an extension of their application to infants; as discussed above, overall cancer risk following *in utero* exposure is judged to be no greater than that following exposure in early childhood. The dose criteria are also set allowing for differences between age groups and so for practical radiation protection purposes the use of a single set of tissue weighting factors remains appropriate.

In many situations, direct measurements of external and internal exposures of the public are not available and the assessment of effective dose is carried out using modelling techniques supported where possible by measurements of ambient dose equivalent rate and concentrations of radionuclides in the environment. Rarely, information is also available from personal dosimeters or from measurements of the radionuclide content of individuals through techniques such as whole body counting. Methodologies for assessing doses to the public often adopt cautious parameter values to ensure that doses are not underestimated and therefore to ensure compliance with the relevant dose limits or constraints. It is important that the degree of caution is recognised and care is needed in using the results of such methodologies for optimisation purposes as this might lead to bias in the assessment. This is particularly important when determining whether actions, such as evacuation or decontamination, are required in an emergency exposure situation. It is important to balance the reduction in doses with any deleterious effects of the action and a cautious assessment of doses could lead to unnecessary actions with consequences for the affected population.

In modelling of radionuclide transfer in the environment and especially of internal doses received by members of the public, an important issue is selection of the most appropriate physical and chemical radionuclide characteristics. This consideration is of particular importance for prospective assessment of pre-operational facilities and for emergencies. In both cases, learning from previous experience of similar situations is likely to be instructive, when monitoring data and information on radionuclide characteristics are available. ICRP advise that dose coefficients relevant to specific chemical forms of radionuclides should be used whenever the relevant information is available and the assessment warrants such consideration. When no monitoring data are available, the cautious approach for dose assessment is the selection of those radionuclide characteristics and dose coefficients that result in higher dose estimations. Some guidance on this issue is given in Publication 72 (ICRP, 1996a).

3.3 Collective doses

As discussed in Section 2, collective effective dose is used in the optimisation of protection. The quantity is particularly valuable in occupational radiological protection, for use, for example, in planning complex work involving varying numbers of workers. Collective effective dose can be used to determine the optimum balance between relatively large exposures to a few workers and smaller exposures to a larger number of workers.

For public exposures, collective effective doses can be used as part of the optimisation process for planned exposure situations. They also have a useful role in comparative studies

to consider the radiological impact of different sources of exposure or the effects of adopting different systems of treatment for radioactive wastes.

As discussed in Section 2, collective dose is not intended as a tool for the prediction of health effects in populations and epidemiological analysis and particular care is needed in interpreting collective dose data made up of very low (μSv or nSv) levels of individual dose received over long time periods by large numbers of people. In addition to the uncertainties associated with such collective dose estimates, and uncertainties in any associated health risks, it can be problematic to contextualise estimates of health risk and to make meaningful comparisons. However, there can be situations where the estimation of health effects from collective doses can be useful if treated with appropriate caution. For example, following a severe nuclear accident or in advance planning for such events, an assessment of collective dose could be used to give an indication of possible health impact to help with planning. In retrospective assessments of planned or existing exposure situations, an assessment of collective effective dose and possible associated health impact can provide an initial screening to determine if epidemiological analyses are likely to be warranted. It is essential that such analyses using collective dose include consideration of background rates of health effects in the population, including morbidity and mortality, and consider uncertainties, recognising that health effects in individuals exposed to low levels of radiation are highly unlikely to be attributable to radiation exposure (UNSCEAR, 2012a) and that comparisons with natural disease incidences determine whether epidemiological analyses may provide statistically significant results for populations.

As discussed in *Publication 103* (ICRP, 2007a), it is recommended that when exposures occur over large populations, areas and time periods, such that individual doses range over several orders of magnitude, the collective dose should be split according to ranges of individual dose, also taking account of geographical locations and the time-course of dose delivery. However, there are problems in implementing this recommendation for public exposures if, as is usually the case, ingestion of food is an important exposure pathway. In general, the food people consume is not produced in the immediate area but rather it is sourced over large areas on a changing basis. It is generally not possible to gain specific information on where people obtain their food, collective dose estimates are based on food production data, and the distribution of individual doses is not known (Smith *et al.*, 2006). However, collective effective doses can be estimated for specific population groups living in defined geographical areas over different time periods as discussed in *Publication 103* (ICRP, 2007). Per-caput doses can also be estimated corresponding to the collective doses for different population groups which can provide useful input to optimisation and comparative studies (Smith *et al.*, 2006). Assessments of collective dose into the far future are particularly uncertain due to the impact of factors including climate change, changes to human behaviour and population numbers. Therefore, collective dose assessments involving integration of doses over thousands of years into the future, as might be done in assessing the radiological impact of solid waste disposal, are not considered useful.

4. MEDICAL EXPOSURES

Effective dose is used in medical applications both prospectively for justification and optimisation purposes, and retrospectively for assessing institutional performance, demonstrating compliance with dose limits and verifying the outcome of optimization actions. It has been instrumental in raising awareness of dose levels from diagnostic procedures and providing a broad understanding of associated risks. Because stochastic risks vary substantially according to the organs and tissues irradiated in different medical procedures, measurable dose quantities are unable to convey a meaningful indication of the associated relative health detriments. As a result, effective dose has become a vital tool that is used for multiple purposes, including training medical professionals in radiation protection, making informed judgments for justification, optimizing protection by comparing exposures from different examination modalities and techniques, comparing exposure levels across populations, institutions and countries, and potentially for tracking individual patient doses over time, as well in establishing dose constraints for patient carers and for volunteers in medical research. It has provided an invaluable reference for the improvement of radiation protection in medical practice, and gives a means of conveying an indication of radiation dose relating to health detriment that can be understood by clinicians and non-specialists in radiation protection.

However, the application of effective dose in medicine has sometimes extended beyond the framework of radiological protection or dose optimization, in that it has been used to quantify risks to individuals, including predictions and quantification of increases that might be expected in cancer incidence and fatality following exposures. While effective dose is a risk-related quantity, as discussed in Section 2, it is not intended to provide a measure of risk to individuals or specific population groups (Menzel and Harrison, 2012). In this section, the meaningful use of effective dose in medical exposure and its limitations are discussed.

4.1 Effective dose from medical exposures

Effective doses from medical procedures are calculated using dose coefficients that relate measurable quantities to the protection quantities (see Section 2.2). Daily decisions for justifying individual patient imaging exposures, or for optimizing protection through selecting the most appropriate technique, require rough estimates of dose relating to health detriment. Generic values of effective dose for a reference person derived using the coefficients provide a straightforward tool with enough information about general radiation exposure levels linked to detriment for the purpose of making these every day decisions. Examples of effective dose values are given in Table 9; ideally, data that apply to the country and facility under consideration should be used and this is clearly most important in the case of examinations involving radiography and fluoroscopy and CT examinations.

When effective doses are required for individual patients for assessing cumulative exposures over time or evaluating unintended exposures, assessments can be made from measurable dose quantities using conversion coefficients, as described in Section 2.2 (Jones and Wall, 1985; Hart *et al.*, 1994; Ranniko *et al.*, 1997; Kramer *et al.*, 2004; IMPaCT; CTExpo; Wall *et al.*, 2011, Lee *et al.*, 2012; Smith-Bindman *et al.*, 2016; ICRP, 1987, 1998b, 2008; Stabin, 1996; Stabin *et al.*, 2005).

Table 9. Example effective doses (mSv) for adults from medical procedures

Procedure	UK (Wall <i>et al.</i> , 2011; Shrimpton <i>et al.</i> 2016)	USA (Mettler <i>et al.</i> , 2008; Smith- Bindman, 2015)
Radiographs		
Head AP	0.033	0.07
Head PA	0.020	0.02
Head Lat	0.016	0.01
Cervical spine AP	0.018	0.1
Cervical spine Lat	0.012	0.1
Shoulder AP	0.007	0.06
Shoulder axial	0.004	0.04
Chest PA	0.014	0.03
Chest Lat	0.038	0.07
Thoracic spine AP	0.24	1.0
Thoracic spine Lat	0.14	1.0
Lumbar spine AP	0.39	2.0
Lumbar spine Lat	0.21	2.0
Lumbo-sacral joint	0.17	0.25
Abdomen AP	0.43	0.7
Pelvis AP	0.28	1.25
Single Hip	0.087	0.07
Both Hips	0.19	0.14
Femur AP	0.011	0.06
Femur Lat	0.001	0.06
Knee AP	0.0001	0.005
Knee Lat	0.0001	0.005
Foot (dorsi-plantar)	0.0001	0.001
Foot (oblique)	0.0001	0.001

Examinations involving radiography and fluoroscopy

Barium swallow	1.5	3
Barium follow through	1.3	4.5
Barium enema	2.2	8
Coronary angiography	3.9	15
Femoral angiography	2.3	7

CT examinations

CT Head	1.8	2.1
CT Chest	14	11
CT Abdomen	16	
CT Abdomen + Pelvis	13	17
CT Chest + Abdomen + Pelvis	19	29

When imaging is limited predominantly to one anatomic area, such as in mammography of the breast, estimates of organ dose may be required rather than, or in addition to, effective

dose. Similarly, assessments of doses from imaging procedures involving iodine uptake by the thyroid should primarily be quoted in terms of thyroid dose, which is the predominant organ irradiated. In addition, gonad dose should be used for evaluation of examinations in which doses to the reproductive organs make up the majority of the dose, rather than effective which relates to an average dose for the gonads in the two sexes.

4.2 Justification of medical practices and procedures

The decision to prescribe medical imaging should be driven primarily by the expected clinical benefit. Nonetheless, there is a broad belief that a significant proportion of examinations may not be indicated clinically. Consequently, there is a growing movement in the USA, Europe and many other countries worldwide to try to decrease the proportion of unnecessary medical imaging, which has been estimated to make up as much as 30% of all examinations (US: American Board of Internal Medicine Foundation; and EUROPE).

ICRP (1996b, 2007b, 2008) recommends justification of medical exposures at three levels: 1) that use of radiation in medicine should do more good than harm, 2) that a given type of procedures is justified for a particular clinical indication as it will improve the diagnosis or treatment of patients; and 3) that a medical examination for an individual patient will do more good than harm, by contributing to the management of the patient's treatment. The first level of justification occurs at national level when radiation equipment and techniques are approved for purchase and use in hospitals. The second level is reflected in referral guidelines produced by professional societies and health authorities, and here effective dose is used to provide information on the relative magnitudes of doses from different kinds of examination that must be balanced by the clinical value added through delivery of the test (Reference American College of Radiology Appropriateness Criteria; EU, 2000; EANM guideline series). Clinicians are responsible for carrying out the third level of justification for every patient for whom an imaging procedure that uses ionizing radiation is requested, based on the patient's clinical history. The diligence with which physicians justify examinations varies by country and should depend on the radiation risk and the procedures used.

Values of effective dose for the reference patient included in guidelines for referral and justification are appropriate for the guidance of physicians requesting and performing examinations. In addition to values for adults, effective doses are also available for limited ranges of paediatric examinations based on x-ray exposure factors or administered activity, as dose distributions within the smaller bodies of children can differ considerably from values obtained for adults. More complex calculations are unnecessary for the purpose of justification.

4.3 Optimization of protection

The optimisation of radiological protection for patients in medicine is usually applied to the design, appropriate selection, and construction of equipment and installations; and to the day-to-day choice of techniques and procedure parameters (i.e. the clinical protocols). The basic aim of the optimisation is to adjust the protective measures in such a way that the net benefit is maximised, by obtaining the desired medical objective in the provision of all the diagnostic information required while keeping the radiation dose to a minimum (ICRP, 2008).

Comparison of patient exposure from different procedures and techniques

Patient imaging procedures typically involve partial body radiation exposures to tissues with differing sensitivities in terms of radiation-associated cancer. However, the amount of radiation and the distribution within the tissues can be very different, even when a similar region of the body is being imaged. For example, whereas a chest CT examination and a conventional chest x-ray will both irradiate the lungs, the effective dose from the CT will be a few hundred times that from the radiograph, and the distribution will also be different. For example with a postero-anterior (PA) projection chest radiograph the dose from scattered radiation to the breasts could be a factor of many thousand less than that from a chest CT, while the effective dose could be a factor of five hundred lower. If the same information is provided by a chest CT or chest radiograph for a particular clinical question, effective dose differences (even if crudely estimated) will provide powerful information that will support using the radiograph.

Measureable dose quantities rather than effective dose are generally more useful for making dose comparisons between different techniques that deliver exposures with similar relative distributions of absorbed dose inside the body. For this, quantities such as ESAK and KAP for radiography and fluoroscopy, and volume averaged CT dose index ($CTDI_{vol}$) and DLP for CT should be used. However, when dose distributions are substantially different, such as when using a different radiographic projection, using different tube potentials (kVs), or very different x-ray tube filtration – for example in interventional procedures - effective dose to a reference patient will be the appropriate quantity for optimizing protection, as it accounts for the differing contributions of organs and tissues to overall radiation detriment (see Section 2.1). One example is comparison of antero-posterior (AP) and PA projections, as the dose distribution inside the body will change and so the relative doses to the exposed organs will be different. Organs lying closer to the surface on which the x-rays are incident will receive higher doses. Another example is the selection of kV or filtration for an x-ray examination, where increasing the kV will give more penetrating radiation, so that the exposure level can be reduced, lowering the dose to more superficial tissues, while the effect on doses to tissues deep within the body near to the image receptor will be minor (Martin, 2007b; Martin, 2008; Martin and Sutton, 2014). The determination of effective dose allows the creation of a catalogue of radiation exposures from different procedures that can then be used to inform choices on the appropriate type of examination to solve particular diagnostic questions.

Since dose distributions from radiological and nuclear medicine procedures are obviously very different, here effective dose is the only dose quantity suitable for making comparisons and informing decisions about risks from the different methodologies.

Comparison of patient doses for the same procedures across institutions and countries

Comparisons of exposure among different hospitals and even different countries are often made in surveys to establish diagnostic reference levels (DRLs) against which dose comparisons can be made to judge whether radiation protection is optimised. They may also be measured during research projects with the purpose of revealing differences in dose and finding reasons for these differences in order to identify optimization opportunities. Examples of this application are national and international surveys (EU, USA, IAEA, Public Health England). Such surveys are best reported in terms of measured quantities such as KAP, ESAK, $CTDI_{vol}$ and DLP, and the DRLs that form part of the optimisation process should be set in terms of these measurable quantities (Martin, 2008; Martin, 2011b; ICRP, 2016), since

derivations of effective dose introduce calculations and approximations that are unnecessary for this purpose.

In official international reporting of the uses of radiation and the sources of exposure to the UN, as done by UNSCEAR, use of the measurable quantities is again useful. However, in addition, comparison of effective dose to different populations may also be made in terms of effective dose per caput and collective effective dose.

Tracking cumulative patient exposure

The use of medical imaging has increased rapidly in the US and Europe in recent decades. As an example, Patient exposure to radiation from medical imaging in the USA has increased approximately 6 fold in the last 15 years and currently around 20-25 CT scans are performed annually per 100 individuals (Smith-Bindman, 2009). Effective doses from medical diagnostic exposures received by individuals in some countries are within the range of tens of mSv or even 100 mSv and greater (Jaffe *et al.*, 2007; Griffey *et al.*, 2009; Cook *et al.*, 2010; Smith-Bindman *et al.*, 2012; Miglioretti, 2013). In order to provide more formal methods for quantification of these doses and enable individuals receiving higher doses to be identified more readily, methods are being developed for recording patients' accumulated radiation exposure from medical imaging procedures over time (Rehani *et al.*, 2014; Rehani, 2015). This is advisable in large part because there has been less oversight and standardization in the justification of individual exposures. While the justification is primarily driven by the clinical indication, knowledge of an individual's cumulative dose from medical exposures, even if imprecise, should help focus efforts to avoid unnecessary imaging and dose reduction.

Effective dose can be estimated for different types of examinations and so has potential for use in patient dose tracking. This would require calculation at the time of the examination and may become easier over time through the widespread use of patient dose management software that permits the calculation of effective dose from different exposures and inclusion of these data in electronic health records. It has also been suggested that adjustments could be made to account for differences in body dimensions from those of the reference person (i.e. for patients who are larger or smaller than the reference person). However, the result could not formally be called effective dose and the adjustments resulting from such considerations of body mass are small in comparison with uncertainties in the associated detriment and variation between individuals in inferred risks at low doses (see below). It is most appropriate, therefore, to estimate effective dose according to its formal definition, either for adults or for children for which reference parameters and models are provided.

Radiology imaging equipment provides measured or calculated dose data for radiography and fluoroscopy (KAP), and for CT (DLP.) These dose quantities allow medical physicists to estimate organ and effective doses and should be recorded. However, in order to provide dose information that can be more readily interpreted in terms of possible risk, and more readily understood by clinicians and others, effective dose for the reference person provides an appropriate metric, based on a simple conversion factor from DLP or KAP. Since risks of radiation-induced cancer vary with age (Section 2.1 and below), recording age at exposure will be helpful in enabling simple adjustments to be made to account for changes in overall detriment per Sv.

Doses to carers and volunteers in medical research

Exposures (other than occupational) incurred knowingly and willingly by individuals helping in the support and comfort of patients undergoing diagnosis or treatment are considered as medical exposure. A typical example is the exposure of family members of a patient discharged after a thyroid treatment with unsealed ^{131}I , or patients who still retain implanted sealed sources. Assessments of potential exposures and doses received will need to be made from time to time, and the appropriate quantity, as for occupational and public exposures is effective dose.

In a similar way, exposures incurred by volunteers as part of a programme of biomedical research are also considered to be medical exposures (ICRP, 1991b, 2007b; IAEA, 1995, 2011). An example is the performance of imaging procedures that are planned for evaluation of the effectiveness of treatments in research studies for groups of patients. Before a research proposal is approved an evaluation of possible detriment for the individuals involved must be made and recorded prior to justification. Effective dose is the appropriate quantity to use for summing the possible health detriments that may accrue from the various procedures, which may have different dose distributions inside the body (IAEA, 2011).

4.3 Effective dose and risk estimation

Effective dose has proved to be a useful tool in controlling exposures received by patients undergoing medical diagnostic and interventional procedures. However, its use to provide estimates of risk to individual patients goes beyond its intended use (ICRP, 2007a; Menzel and Harrison, 2012). Brenner (2008, 2012) has suggested that effective dose should be replaced by effective risk as a more scientifically based quantity. Unfortunately, this approach ignores the uncertainties associated with the LNT dose-response relationship as applied to all cancer types and gives a misleading impression of our ability to quantify risks at low doses. A clear distinction should be drawn between the application of science in the definition of the risk-adjusted protection quantity, effective dose, which has proved to be of considerable practical utility, and the use of best scientific information to calculate risks to individuals and population groups. Risk estimation can be specific to individuals of known body mass and dimensions, applying age and sex specific risk factors derived for the most appropriate population group. An example is NASA estimates of risk to individual astronauts (Harrison, 2015). Such scientific best estimates of risk should also consider associated uncertainties.

Although effective dose was not intended as a measure of risk to individuals, it can reasonably be used as a rough indicator of possible risks, both in general terms for risk communication, and to provide information on possible risks to individuals, with appropriate caveats.

Communication of risks to clinicians and patients

For discussions regarding justification and optimisation of examinations and for communication with patients, clinicians need language that reflects a broad perspective of risk, and this can be provided through effective dose. A scale linked to effective dose, giving general terms to describe the possible level of risk is given in Table 10, together with examples of procedures within different risk categories. For example, the risk from an exposure giving an effective dose of 10 to 20 mSv can be termed low, while that for effective doses in the range 1 mSv to 10 mSv can be considered to be ‘very low’ equating to the

exposures individuals get every year simply from living on earth through exposure to natural background radiation. The excess risk from an effective dose less than 0.1 mSv, which includes examinations such as chest x-rays, is categorized as negligible.

Table 10. Dose ranges and terminology for describing risks from different medical procedures for patients of average age (30-39y) based on UK data (Martin, 2007; Wall *et al.*, 2011; Martin and Sutton, 2014)

Effective doses (mSv)	Nominal risk range based on LNT model ^a	Proposed risk term	Examples of medical radiation procedures within different dose categories ^b
< 0.1	< 10 ⁻⁵	Negligible	Radiographs of chest, femur, shoulder limbs, neck, and teeth, , ^{99m} Tc sentinel node imaging, radionuclide labelling for in vitro counting with ¹⁴ C and ⁵⁷ Co.
0.1–1	10 ⁻⁵ – 10 ⁻⁴	Minimal	Radiographs of spine, abdomen, pelvis head and cervical spine, radionuclide labelling for in vitro counting with ⁵¹ Cr. ^{99m} Tc for imaging lung ventilation and renal imaging.
1–10	10 ⁻⁴ – 10 ⁻³	Very low	Barium meals, , CT scans of the head and combinations of chest, abdomen, and pelvis, barium enemas, cardiac angiography, interventional radiology;; ^{99m} Tc myocardial imaging, and SPECT imaging of lung perfusion ^{99m} Tc for imaging lung perfusion ^{99m} Tc imaging of bone lesions, and cardiac stress tests; imaging with ¹⁸ F, ¹²³ I, and ¹¹¹ In, ^{99m} Tc SPECT imaging
10–100	10 ⁻³ – 10 ⁻²	Low	CT scans of chest, abdomen, and pelvis, double CT scans for contrast enhancement, interventional radiology; ⁶⁷ Ga tumour, and ²⁰¹ Tl myocardial imaging; multiple procedures to give doses of 10s mSv.
100s	10 ⁻²	Moderate	Multiple procedures

^aRisks estimated to nearest order of magnitude.

^bEffective doses in the UK.

The benefits of medical exposure in general are greater than the small risks relating to possible long-term health effects. As a result, clinicians who prescribe and perform medical procedures involving radiation may have little understanding of the potential health detriment from radiation exposure. Without this knowledge, they cannot take the health effects into account when requesting or justifying patient diagnostic or interventional exposures, nor when explaining the low risks to their patients. Effective dose provides a useful metric for communication with clinicians and patients.

Clinicians and patients will sometimes need more information in order to put radiation exposures and possible risks into context. For this, comparisons with radiation doses from other situations with which the individuals are familiar, and for which they accept the risk, can be helpful. Examples of everyday exposures are those from exposure to natural background radiation and the dose that an individual might receive from cosmic rays during a flight. These comparisons can be particularly useful in explanations for patients who have concerns about the procedures that they are undergoing, but have little or no knowledge about radiation and may as a result have an unrealistic fear of the potential harm from a radiation exposure. Thus the quantity effective dose can be instrumental in educating medical

practitioners, patients and the public, by helping to provide a broader perspective of the risks from use of radiation. There is generally no need to specify risk of cancer incidence or cancer mortality. However, approximate quantification of risk might be appropriate in particular circumstances, bearing in mind that risk estimates applied to low doses depend on the applicability of risk factors derived for higher dose exposures.

Age- and sex- specific cancer risks and effective dose

As discussed in Section 2.1, epidemiological data used to provide risk estimates for radiation-induced cancer show differences in risk between males and females and as a function of age at exposure. Depending on the risk projection models used, there are also differences between populations. While risks are estimated to be similar for males and females for some cancers, including stomach, bladder, liver and leukaemia, risks for females are greater than for males in a number of cases, notably breast cancer, but also lung and thyroid cancers (Tables 4 and 5). In general, risks compared with those for the 30-39y age-group are greater by a factor of about two for exposures of young children, aged 0-9 y, and less by a factor of two for exposures of older adults, aged 60-69y (Tables 5 and 6). Within this general trend, some cancer types show greater age-dependence, notably thyroid cancer, while others show little or no age-dependence, including lung cancer.

Wall *et al.* (2011) use the risk data presented in Table 4, applying to the ICRP Euro-American composite population, together with UK estimates of organ doses from a range of medical procedures, to calculate age- and sex- specific risks from these procedures. Dividing these risk estimates by corresponding values of effective dose for each procedure gave the values reproduced in Table 11. Similarly, using the risk data presented in Table 5 for the ICRP Asian composite population, the calculated values of age- and sex- specific risks per Sv are as shown in Table 12. For males and females and each population, variations in risk per Sv reflect the combination of organ doses relating to each procedure. Figure 3 presents the data from Table 5 together with the risks per Sv for uniform whole body irradiation from Table 4. Overall, the data show a similar pattern for most procedures, with risks for individual procedures generally within about $\pm 50\%$ of those for uniform whole-body irradiation.

It is important that the precision that might be inferred from the values presented in Tables 11 and 12 does not give a false impression of the reliability of estimates of cancer risk from low dose radiation exposures. The detailed data are included here to illustrate the overall pattern of age and sex differences in estimated risk. On the basis of these data, it can be concluded that when considering most x-ray examination, risk per Sv may be around twice as great for the 0-9 y age group than the 30-39y group, for which risks are closest to ICRP nominal coefficients (Table 2). For patients in their 60s, the risk coefficients for most examinations are about half those for patients in their 30s, falling to less than one-third for patients in their 70s and about one-tenth for those in their 80s. Wall *et al.* (2011) identified a small number of examinations that might be regarded as deviating significantly from this pattern, as illustrated in Figure 4. Bearing in mind the substantial uncertainties associated with projections of low dose risk, it is considered reasonable to consider such variations in possible risk per Sv effective dose in conveying information to clinicians and patients.

Table 11. Total lifetime cancer risk (%) per Sv effective dose as function of age at exposure and sex for a range of x-ray examinations, calculated using risk data for the ICRP Euro-American composite population (from Wall *et al.*, 2011)

Examination	Sex	Age at exposure (y)									
		0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99
Head	M	17	12	8.7	6.4	4.7	3.2	1.8	0.9	0.4	0.0
(AP+PA+Lat)	F	16	11	7.8	5.4	4.2	2.7	1.5	0.7	0.3	0.0
Cervical spine	M	9.1	6.2	4.1	2.8	2.0	1.3	0.8	0.4	0.2	0.0
(AP+Lat)	F	20	12	7.2	4.2	2.6	1.6	1.0	0.5	0.2	0.0
Chest	M	8.7	7.4	6.2	5.5	5.0	4.3	3.2	2.0	0.9	0.1
(PA)	F	13	11	9.6	8.8	8.6	7.5	5.7	3.5	1.3	0.0
Thoracic spine	M	7.8	6.4	5.2	4.6	4.1	3.4	2.5	1.6	0.7	0.0
(AP+Lat)	F	17	13	11	8.8	7.8	6.5	4.8	2.9	1.1	0.0
Abdomen	M	13	10	8.1	6.4	4.9	3.5	2.2	1.1	0.4	0.0
(AP)	F	12	9.2	7.3	5.8	4.5	3.3	2.2	1.2	0.4	0.0
Pelvis	M	11	8.8	7.0	5.7	4.5	3.3	2.1	1.1	0.4	0.0
(AP)	F	8.4	6.8	5.5	4.5	3.6	2.7	1.8	1.0	0.4	0.0
Lumbar spine	M	12	9.4	7.2	5.7	4.4	3.1	1.9	1.0	0.4	0.0
(AP+Lat)	F	11	8.6	6.8	5.3	4.3	3.1	2.0	1.1	0.4	0.0
IVU	M	12	9.8	7.6	6.0	4.5	3.2	2.0	1.0	0.3	0.0
	F	11	9.0	7.1	5.6	4.3	3.1	2.0	1.1	0.4	0.0
Ba swallow	M	8.3	6.3	4.8	3.8	3.0	2.3	1.6	1.0	0.4	0.0
	F	19	13	9.5	7.0	5.4	4.0	2.8	1.7	0.6	0.0
Ba follow	M	13	10	8.0	6.3	5.0	3.6	2.3	1.2	0.5	0.0
	F	11	8.7	6.9	5.5	4.7	3.3	2.1	1.1	0.4	0.0
Ba enema	M	12	9.6	7.5	6.1	4.9	3.7	2.3	1.3	0.5	0.0
	F	9.2	7.4	6.0	4.8	4.3	3.0	2.0	1.1	0.4	0.0
Coronary angiography	M	8.6	7.5	6.4	5.9	5.5	4.8	3.7	2.4	1.0	0.1
	F	11	10	9.5	9.2	9.4	8.6	6.8	4.3	1.7	0.0
Femoral angiography	M	12	9.9	7.4	6.1	5.0	3.8	2.5	1.4	0.6	0.1
	F	9.4	7.5	6.1	4.9	4.7	3.2	2.0	1.1	0.4	0.0
CT head	M	18	14	9.5	7.3	5.7	4.1	2.6	1.4	0.6	0.1
	F	13	9.9	7.5	5.5	5.1	3.3	1.9	1.0	0.3	0.0
CT chest	M	8.0	6.6	5.3	4.6	4.0	3.3	2.4	1.5	0.6	0.0
	F	17	13	10	8.5	7.3	6.0	4.4	2.6	1.0	0.0
CT abdomen	M	12	9.4	7.2	5.6	4.3	3.1	1.9	1.0	0.4	0.0
	F	11	8.5	6.7	5.3	4.3	3.1	2.0	1.1	0.4	0.0
CT abdomen + pelvis	M	13	10	7.8	6.2	4.9	3.5	2.2	1.2	0.4	0.0
	F	11	8.9	7.1	5.6	4.7	3.4	2.2	1.2	0.4	0.0
CT chest + abdo + pelvis	M	9.6	7.8	6.2	5.2	4.3	3.4	2.4	1.4	0.6	0.0
	F	15	11	9.1	7.4	6.3	5.0	3.6	2.1	0.8	0.0

Table 12. Total lifetime cancer risk (%) per Sv effective dose as function of age at exposure and sex for a range of x-ray examinations, calculated using risk data for the ICRP Asian population (based on Wall *et al.*, 2011)

Examination	Sex	Age at exposure (y)									
		0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99
Head	M	11	8.2	5.9	4.4	3.4	2.3	1.5	0.8	0.4	0.0
(AP+PA+Lat)	F	17	11	7.9	5.4	4.3	2.6	1.5	0.7	0.3	0.0
Cervical spine	M	6.7	4.4	3.0	2.1	1.5	1.1	0.7	0.4	0.2	0.0
(AP+Lat)	F	25	15	9.0	5.1	3.1	1.8	1.0	0.5	0.2	0.0
Chest	M	8.7	7.6	6.6	5.9	5.5	4.7	3.7	2.3	1.0	0.0
(PA)	F	14	11	10	8.9	8.6	7.4	5.9	3.9	1.8	0.0
Thoracic spine	M	7.8	6.7	5.7	5.0	4.5	3.8	2.9	1.8	0.8	0.0
(AP+Lat)	F	19	14	11	9.2	8.0	6.5	5.0	3.2	1.5	0.0
Abdomen	M	13	11	8.7	6.8	5.3	3.7	2.3	1.1	0.4	0.0
(AP)	F	12	10	8.1	6.3	5.0	3.6	2.4	1.3	0.5	0.0
Pelvis	M	9.1	7.4	6.0	4.8	3.8	2.7	1.7	0.9	0.4	0.0
(AP)	F	7.2	5.8	4.8	3.8	3.2	2.4	1.6	0.9	0.4	0.0
Lumbar spine	M	13	11	8.6	6.8	5.3	3.7	2.3	1.1	0.4	0.0
(AP+Lat)	F	12	9.8	8.0	6.2	5.0	3.6	2.4	1.3	0.5	0.0
IVU	M	14	11	8.8	6.9	5.3	3.7	2.2	1.1	0.4	0.0
	F	13	10	8.4	6.5	5.1	3.6	2.3	1.3	0.5	0.0
Ba swallow	M	8.2	6.4	5.1	4.2	3.4	2.6	1.9	1.1	0.5	0.0
	F	22	15	11	7.9	6.1	4.4	3.1	1.9	0.8	0.0
Ba follow	M	13	10	8.1	6.5	5.2	3.7	2.4	1.3	0.5	0.0
	F	11	9.0	7.3	5.7	5.0	3.5	2.2	1.2	0.5	0.0
Ba enema	M	10	8.5	6.8	5.5	4.5	3.3	2.1	1.2	0.5	0.0
	F	8.3	6.7	5.5	4.4	4.0	2.8	1.8	1.0	0.4	0.0
Coronary	M	8.6	7.8	6.9	6.4	6.0	5.3	4.2	2.7	1.2	0.0
angiography	F	11	10	9.6	9.1	9.3	8.4	7.0	4.7	2.2	0.0
Femoral	M	11	9.2	7.2	5.9	4.9	3.7	2.5	1.4	0.6	0.0
angiography	F	9.0	7.2	6.0	4.8	4.8	3.2	2.0	1.1	0.4	0.0
CT head	M	12	9.4	6.8	5.4	4.5	3.3	2.3	1.3	0.6	0.1
	F	12	9.1	7.1	5.3	5.1	3.3	1.9	1.0	0.4	0.0
CT chest	M	8.6	7.2	6.1	5.2	4.6	3.8	2.8	1.7	0.7	0.0
	F	18	14	11	9.0	7.7	6.2	4.7	3.0	1.3	0.0
CT abdomen	M	13	11	8.5	6.7	5.2	3.7	2.3	1.1	0.4	0.0
	F	12	9.8	8.0	6.2	5.1	3.6	2.3	1.2	0.5	0.0
CT abdomen +	M	13	10	8.3	6.6	5.2	3.7	2.3	1.2	0.5	0.0
pelvis	F	12	9.5	7.7	6.0	5.1	3.6	2.4	1.3	0.5	0.0
CT chest +	M	9.8	8.1	6.7	5.6	4.7	3.7	2.6	1.5	0.6	0.0
abdo + pelvis	F	16	12	9.7	7.7	6.6	5.1	3.8	2.3	1.0	0.0

Fig. 3. Total lifetime cancer risk per unit effective dose as a function of age at exposure and sex for a range of x-ray examinations (Table 11) and for uniform whole body exposure (Table 4) (from Wall *et al.*, 2011).

Fig. 4. Total lifetime cancer risk per unit effective dose as a function of age at exposure and sex for the 5 x-ray examinations significantly different from uniform whole body exposure (from Wall *et al.*, 2011).

The use of effective dose to provide an approximate indication of possible risk associated with medical procedures is not a substitute for detailed assessments of risk for individuals or specific population groups. Risk assessment will always be based on measurements or estimates of mean absorbed doses to individual organs and use age- and sex- specific risk coefficients for the most appropriate population group. For detailed analyses, absorbed dose estimates should take account of the size of the patient and other factors influencing the distribution of radiation dose within the patient's organs. For CT scans, doses to larger organs and ones that are located centrally within the scanned region decrease exponentially with trunk diameter (Li *et al.*, 2011). Particular care should be taken when deriving doses for organs and tissues which lie near the boundary of the exposed region of the body, since these can vary substantially with small changes in exposure conditions. Patient specific organ doses for CT may be calculated from sectional image data for the examination (Li *et al.*, 2011) or adjustments to organ doses made based on patient dimensions or weight (Huda and He, 2012). Uncertainties in both dose and risk estimates should be considered.

Situations of unintended exposure and overexposure of patients, in which assessments of risk are required, provide examples of the use of effective dose as an indicator of risk and the requirement for specific risk estimation. An unintended exposure could occur in various situations, such as when the exposure has not been justified, when there has been an error in the referral process or the wrong patient was examined. An overexposure might occur when there has been a mistake in the procedure technique, or where an equipment fault has occurred (Martin, 2005). In situations of unintended exposure, a broad assessment in terms of effective dose may be sufficient. If the unintended exposure is known to be similar to the dose for the examination being carried out, then generic values of effective dose can be used for doses lower than 1-2 mSv. When the effective dose is greater or exposure conditions do not equate to a standard examination, it is more appropriate to calculate the effective dose from the available exposure data. If there is a perceived need for a more in-depth treatment involving an assessment of risk for the individual from a higher dose exposure, then doses for all radiosensitive organs and tissues should be estimated, and combined with age, sex and organ specific risk coefficients to derive a best estimate of risk; uncertainties should be assessed.

5. SUMMARY and CONCLUSIONS

The Introduction to this report raised a number of issues for which clarification and guidance were considered to be needed. This final section expands on the information provided as main points in the front of the document, answering the issues raised in the Introduction and draws together the conclusions reached.

Effective dose (E) in sievert (Sv) is accepted internationally as the central radiological protection quantity, providing a risk adjusted measure of total body dose from external and internal sources in relation to stochastic risks of cancer and hereditary effects, expressed in terms of detriment. E has proved to be a valuable and robust quantity for use in the optimisation of protection and setting of control criteria: limits, constraints and reference levels. The use of E relies on the reasonable assumption of a linear non-threshold (LNT) dose-response relationship between dose and risk at low doses, and the equivalence of effect of acute and chronic exposures, and of internal and external exposures. The LNT dose-

response assumption underpins the use of effective dose as a protection quantity, allowing the addition of external and internal doses of different magnitudes, with different temporal and spatial patterns of delivery. However, it should be recognised that while low doses may be measured or estimated with reasonable reliability, the associated cancer risk is uncertain, and increasingly uncertain as dose decreases. The available scientific evidence supports the assumptions of equivalence of acute and chronic exposures from external and internal sources of radiation. Notably, epidemiological data, supported by animal data, indicate that it is reasonable for protection purposes to assume equivalence of risk per unit dose, once simple adjustment are made to account for RBE, between short duration exposures to external penetrating low LET gamma rays and protracted internal exposures to alpha particle emitting radionuclides, for which tissue doses will be substantially more heterogeneous.

Mean absorbed dose averaged over organs and tissues is the primary scientific quantity from which E is calculated. Absorbed dose in gray (Gy) should be used to set limits on organ/tissue doses to prevent tissue reactions (deterministic effects) rather than equivalent dose which relates to stochastic effects. Equivalent dose to organs and tissues (Sv) is obtained by multiplying absorbed dose by radiation weighting factors (w_R) to account for the relative effectiveness of different radiation types in causing stochastic effects. Equivalent dose can be seen as an intermediate step in the calculation of E and it is proposed that its use as a separate protection quantity should be discontinued.

Currently, equivalent dose is used to set limits for the avoidance of deterministic effects in the cases of irradiation the hands and feet, lens of the eye, and skin; that is, limits set below thresholds for the occurrence of acute damage to organs and tissues. However, available data indicate that differences between radiation types (eg alpha particles and neutrons cf. gamma rays) in their effectiveness per Gy in causing deterministic effects are smaller than differences in their effectiveness in relation to cancer induction. It can and has been argued, therefore, that use of equivalent dose limits to prevent deterministic effects is overly conservative and that specific lower radiation weighting factors should be applied. While it is important to recognise this conservatism, it is concluded that this is not of great practical concern in most cases and the complexity of introducing further quantities with different radiation weighting factors is not warranted. A distinction should be drawn between reasonable conservatism as applied to the use of protection quantities to set limits for planned exposure situations and scientific judgements of the likelihood of observable effects in specific circumstances. However, it is proposed here that limits for the avoidance of deterministic effects will be more appropriately set in terms of absorbed dose (Gy). The limits for the lens of the eye, skin and hands and feet are relevant mainly to circumstances of exposure to penetrating low LET radiations, and to the extent that they will also be applied to radiations of greater effectiveness per Gy, the conservatism introduced in setting the limits will compensate for any such small differences. This change would not require changes to the numerical values of dose limits.

The control and limitation of stochastic effects rely almost entirely on the use of effective dose. To the extent that it is necessary to consider organ and tissue doses separately, they are better expressed in terms of absorbed dose in gray (Gy), avoiding any potential confusion with effective dose in sievert (Sv). For example, an intake of iodine-131 might result in an effective dose of 10 mSv, largely contributed by a thyroid dose of 240 mGy (low LET). The discontinuation of the use of equivalent dose as a separate protection quantity will also avoid understandable confusion between this quantity and dose equivalent (Sv), the measured

quantity for external radiation used as an estimate of effective dose; the words dose and equivalent used together will then more readily be understood to refer to the operational quantity.

The radiation weighting factors (w_R) used in the calculation of equivalent doses are intended to provide a readily applicable and simple scheme to take account of the differing effectiveness per Gy of different radiations in causing stochastic effects. Attention has been drawn to apparent inconsistencies in the setting of w_R values, with a simple approach for all low LET radiations and alpha particles but greater complexity for neutrons, and furthermore, the use of a different approach using quality factor in calculating operational quantities for neutron exposures. A w_R value of 1 is used for all low LET radiations, despite recognised differences by factors of around 2 – 3 in RBE values for cancer-related end-points (Hill, 2004; Harrison and Day, 2008), because greater complexity was not judged to be necessary or helpful for protection purposes. Similarly, a w_R of 20 is applied to all alpha particle exposures, although experimental and epidemiological evidence suggests that lower values apply to particular cancer types, including leukaemia induction by irradiation of the red bone marrow. In contrast, neutron w_R is presented as an energy dependent function, differing from the energy dependent quality factor based on LET used in the calculation of the operational quantities. However, while plausible simplifications have been suggested, the energy dependent function of neutron w_R provided in Publication 103 (ICRP, 2007) is consistent with available physical and biological data, taking account of the varying contributions of low and high LET radiations. The operational quantities specified by ICRU have the advantage of continuity of approach and importantly, current assumptions lead to reasonably conservative estimation of effective dose by measurements of dose equivalent.

Nominal stochastic risk coefficients and corresponding detriment values, to which E relates, are calculated for a composite of seven Euro-American and Asian populations, applying to uniform whole-body exposures to external (low LET) radiation of a population of both sexes and all ages. Internationally applicable values are provided for all workers (18-65y) and the whole population. Tissue weighting factors (w_T) used in the calculation of effective dose are a simplified representation of relative detriment values, relating to detriment for the whole population; that is, simplified adjustments to take account of the contribution of individual organs and tissues to overall stochastic detriment. E is calculated for sex-averaged Reference Persons of specified ages. The Publication 103 definition includes the specification of reference male and female anatomical models for radiation transport calculations. While exposures may relate to individuals or population groups, E is calculated for Reference Persons exposed in the same way.

For the operation of the protection system, it is of considerable utility to be able to set protection criteria that apply to all members of the public or all workers. It has been argued that this approach does not adequately protect women and younger children and that differences between males and females and greater risks at younger ages should be reflected more explicitly in the protection system, including the use of different detriment values and w_T values. In this context, it is notable that estimated differences in risk between males and females and between age groups, as illustrated in Tables 4 and 5, are not large in comparison with the uncertainties associated with their estimation. Central to the application of the protection system is optimisation below constraints and reference levels, which should ensure protection of all groups within populations. Protection would not be improved by introducing separate considerations for males and females and children of different ages. A distinction should be drawn between the use of scientific information to construct a workable and

acceptable protection system and the use of science to provide best estimates of dose and risk to individuals and specific population groups (see below). The use of constraints and reference levels that apply to all workers and all members of the public, together with optimisation, provides a pragmatic and workable system of protection that recognises age-, sex-, and population- related differences in risks per Sv but does not distinguish on an individual basis. The only distinction made between males and females for protection purposes is the treatment of occupationally exposed females during declared pregnancy when the fetus is regarded as a member of the public for the purposes of dose limitation (ICRP, 2007). Doses to children and the fetus are considered below.

ICRP dose coefficients are provided as reference values for planning, optimisation of protection and the determination of compliance, and are used for this purpose around the world. While the models used to calculate absorbed doses can be regarded as making best use of available scientific knowledge, they are subject to uncertainties due to the availability of data for their construction. In general, uncertainties for assessments of radiation doses from internal exposures, including the biokinetics of radionuclides and radiopharmaceuticals, are larger than those from external exposures. The degree of uncertainty differs between various radionuclides and radiopharmaceuticals. While the operation of the protection system does not depend on knowledge of such uncertainties, it can be informative to understand the reliability of dose estimates. By design, radiation and tissue weighting factors used in the calculation of effective dose are not best scientific estimates but simplified risk-related adjustments. Effective dose is not a scientific quantity, is not amenable to explicit consideration of uncertainties, and such considerations would not help its application and use within the protection system. In circumstances in which best estimates of dose and risk are required, absorbed dose to organs and tissues would be used, together with RBE data and appropriate age and sex specific risk factors, and in such cases, consideration of uncertainties would be important if not essential.

Publication 103 (ICRP, 2007b) refers to setting of reference levels in relation to emergency planning in the range of 20 - 100 mSv effective dose. In principle, there is no reason why effective doses should not be used as a quantity at doses above 100 mSv: for example, as might be required as a short-term relaxation of worker doses in order to control an accident situation. However, the potential for the occurrence of deterministic effects should be considered and avoided. For effective doses in the low 100s mSv where irradiation is reasonably uniform, severe deterministic effects (tissue reactions) would not be expected to occur, but if there was a significant contribution to the effective dose from radionuclides concentrated in particular organs (eg iodine-131 in the thyroid, inhaled insoluble radionuclides in the lung), tissue damage could occur. Notably, for ^{131}I , for example, an effective dose of 250 mSv could correspond to a thyroid dose of > 6 Gy. A secondary consideration is that for doses in excess of 100 mSv (or more precisely doses to organs and tissues > 100 mGy) delivered at high dose rate, the DDREF of two applied in determining solid cancer risk at low doses will not apply, so that risks may be somewhat greater than might be assumed on the basis of *Publication 103* (ICRP, 2007b) nominal risk coefficients.

ICRP provides effective dose coefficients for situations of external and internal exposures of workers and members of the public, and for radiopharmaceutical administrations to patients, as reference values for use in prospective and retrospective dose assessments. Reference dose coefficients are provided for particular circumstances of exposure, including specific chemical and physical forms of ingested and inhaled radionuclides. Better information on the exposure should be used if available and if the assessment warrants its use. Revision in dose

coefficients due to changes made in ICRP recommendations, including changes to weighting factors, should not require the revision of previous dose assessments.

E is generally calculated for annual exposures, relating to external dose received in the year and committed dose from internal exposures, where committed dose is integrated over a 50y period for workers and to age 70y for members of the public. As discussed in Publication 103 (ICRP, 2007), committed dose is assigned to the year in which the intake occurred. For some radionuclides, with long half-lives and long biological retention times, only a small proportion of the committed dose is delivered in the year of intake. For plutonium-239, for example, effective dose in the first year after intake will be generally less than 10% of the total committed dose. For most radionuclides, however, this effect will be much less significant and for many, including iodine-131 and caesium-137, dose will be delivered entirely or very largely in the year of intake. For practical purposes, the use of committed dose ensures that longer term exposures from intakes of radionuclides are taken into account.

Although effective dose coefficients are provided for a number of age groups of children, it is normally sufficient in public dose assessments to use only the groups 1y, 10y and adults. Representative Person is the term introduced in *Publication 101* (ICRP, 2006b) to replace the concept of “critical group” and is an estimate of effective dose to a hypothetical person of specified age receiving a dose that is representative of the more highly exposed individuals in a population. Effective dose coefficients for the embryo/fetus following intakes of radionuclides are provided for comparison with dose for other age groups to ensure protection of the fetus, showing that it is only in the case of a few radionuclides that fetal doses may need in some circumstances to be considered.

Considering exposures incurred during medical procedures, E is of practical value for comparing: doses from different diagnostic examinations and interventional procedures; the use of similar technologies and procedures in different hospitals and countries; and the use of different technologies for the same medical examination, provided that the representative patients or patient populations for which the effective doses are derived are similar with regard to age and sex. However, as stated in the 2007 Recommendations (*Publication 103*), “... risk assessment for medical diagnosis and treatment ... is best evaluated using appropriate risk values for the individual tissues at risk and for the age and sex distribution of the individuals undergoing the medical procedures”.

E is in widespread use in medical practice as a rough indicator of risk. It is made clear in this report that while doses incurred at low levels of exposure may be measured or assessed with reasonable accuracy, the associated risks are uncertain. However, bearing in mind the uncertainties associated with risk projection to low doses, it is considered reasonable to use E as a rough indicator of possible risk, with the additional consideration of variation in risk with age, sex and population group. Adjustments for the body mass of individual is discouraged as differences in dose and the associated risk are small in comparison with uncertainties in risk projection. Use of E in this way is not a substitute for risk analysis using best estimates of organ doses, appropriate information on the relative effectiveness of different radiation types, and age-, sex- and population- specific risk factors, with consideration of uncertainties.

Data are presented in this report to illustrate variation in cancer detriment per Sv for a range of medical x-ray procedures, assessed using age- and sex- specific risk factors calculated for the ICRP composite Euro-American and Asian populations. It should be recognised that these data are subject to substantial uncertainties inherent in their derivation and application to low

dose radiation exposures. With this important caveat, it can be concluded that when considering most x-ray examination, risk per Sv may be around twice as great for the 0-9 y age group than the 30-39y group, for which risks are closest to ICRP nominal coefficients (Table 2). For patients in their 60s, the risk coefficients for most examinations are estimated to be about half those for patients in their 30s, falling to less than one-third for patients in their 70s and about one-tenth for those in their 80s. For a small number of identified procedures, the age-dependence of risk might be greater (Figure 4). Used appropriately, such information is of value in helping clinicians understand the possible risks associated with examinations and assist in communication with patients.

Collective effective dose is a valuable tool in the optimisation of protection, particularly for occupational exposures. Collective effective dose can be used to determine the optimum balance between relatively large exposures to a few workers and smaller exposures to a larger number of workers. For public exposures, collective effective doses can be used as part of the optimisation process for planned exposure situations. They also have a useful role in comparative studies to consider the radiological impact of different sources of exposure or the effects of adopting different systems of treatment for radioactive wastes.

Collective dose is not intended as a tool for the prediction of health effects in populations and epidemiological analysis and particular care is needed in interpreting collective dose data made up of very low (μSv or nSv) levels of individual dose received over long time periods by large numbers of people. In addition to the uncertainties associated with such collective dose estimates, and uncertainties in any associated health risks, it can be problematic to contextualise estimates of health risk and to make meaningful comparisons. However, there can be situations where the estimation of health effects from collective doses can be useful if treated with appropriate caution. For example, following a severe nuclear accident or in advance planning for such events, an assessment of collective dose could be used to give an indication of possible health impact to help with planning. In retrospective assessments of planned or existing exposure situations, an assessment of collective effective dose and possible associated health impact can provide an initial screening to determine if epidemiological analyses are likely to be warranted. It is essential that such analyses using collective dose include consideration of background rates of health effects in the population, including morbidity and mortality, and consider uncertainties, recognising that health effects in individuals exposed to low levels of radiation are highly unlikely to be attributable to radiation exposure (UNSCEAR, 2012a) and that comparisons with natural disease incidences determine whether epidemiological analyses may provide statistically significant results for populations.

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