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## Use of Dose Quantities in Radiological Protection

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## Published on behalf of the International Commission on Radiological Protection

**Aims and Scope**

The International Commission on Radiological Protection (ICRP) is the primary body in protection against ionising radiation. ICRP is a registered charity and is thus an independent non-governmental organisation created at the 1928 International Congress of Radiology to advance for the public benefit the science of radiological protection. ICRP provides recommendations and guidance on protection against the risks associated with ionising radiation from artificial sources such as those widely used in medicine, general industry, and nuclear enterprises, and from naturally occurring sources. These are published approximately four times each year on behalf of ICRP as the journal *Annals of the ICRP*. Each issue provides in-depth coverage of a specific subject area.

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ICRP is an independent international network of specialists in various fields of radiological protection, typically numbering more than two hundred eminent scientists, policy makers, and practitioners from around the world. ICRP is composed of a Main Commission, a Scientific Secretariat, four standing Committees (on radiation effects, doses from radiation exposure, protection in medicine, and the application of ICRP recommendations), and generally about twenty Task Groups.

The Main Commission consists of a Chair and twelve other members. Committees typically comprise just over 15 members each. Task Groups are usually chaired by an ICRP Committee member and usually contain a number of specialists from beyond the Main Commission and Committees. They are assigned the responsibility for drafting reports on various subjects, which are reviewed and finally approved by the Main Commission. These reports are then published as *Annals of the ICRP*.

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# Annals of the ICRP

ICRP PUBLICATION 147

# Use of Dose Quantities in Radiological Protection

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# CONTENTS

# Editorial

## DOSE AND RISK: SCIENCE AND PROTECTION

The International Commission on Radiological Protection (ICRP) system of radiological protection aims to protect people and the environment from detrimental effects of exposure to ionising radiation. This relies on practical and effective management of radiation doses, which, in turn, relies on clear understanding and proper use of dose quantities.

The system of radiological protection has evolved over more than 90 years, adapting to progress in scientific knowledge about the effects of radiation exposure. Protection of people is based on two protection goals, implemented through application of the fundamental principles of justification, optimisation of protection, and individual dose limitation:

- keeping doses to organs and tissues below thresholds to avoid harmful tissue reactions (deterministic effects); and
- management of effective dose to limit the probability of occurrence of stochastic effects.

The close relationship between dose and health risk is inherent to construction of the system of radiological protection, specifically:

- the relationship between severity of an effect and dose above a threshold for tissue reactions; and
- the relationship between probability of occurrence of an effect and dose without a threshold for stochastic effects.

The system of radiological protection for humans currently uses three dose quantities: absorbed dose, equivalent dose, and effective dose. Absorbed dose to organs and tissues is the fundamental scientific quantity and starting point for calculation of the other risk-adjusted quantities. Equivalent dose to organs and tissues enables the summation of doses from different radiation types, and is currently used to set limits to prevent harmful tissue reactions. Effective dose combines equivalent doses for protection from stochastic effects.

One key point in the present publication is that the Commission now considers absorbed dose to be the most appropriate quantity to use when limiting doses to

organs and tissues to avoid harmful tissue reactions. This draws a clear distinction between limits applying to tissue reactions, set in absorbed dose (Gy), and those applying to stochastic effects, set in effective dose (Sv).

This position is consistent with the approach taken by the US National Council on Radiation Protection and Measurements (NCRP, 2018) and proposals from the International Commission on Radiation Units and Measurements (ICRU, 2020) on changes to operational quantities.

However, ICRP does not recommend an immediate change to the system of radiological protection. Rather, this should be considered an important input into the next fundamental recommendations of the Commission. A review of the system of radiological protection is already underway, aiming to develop the next fundamental recommendations which will supersede *Publication 103* (ICRP, 2007) in about a decade.

For stochastic effects, it is now possible to provide an individual risk assessment taking into account the characteristics of the individual (sex, age at exposure, country of residence) and the dose received (acute or chronic, organs exposed), and thus to make an ad-hoc estimate of the risk for a specific type of cancer. The present publication indicates that this is the approach that should be favoured for risk assessment, using ad-hoc risk models from the epidemiological literature. Variations in health risk with age and sex are illustrated in Tables 2.4 and 2.5 of this publication. It is clear, for example, that the lifetime risk of cancer incurred by a young girl with breast exposure is not of the same nature and magnitude as that of a 60-year-old man with abdominal exposure.

Keeping this in mind, another key point in the present publication is that, under a variety of exposure conditions, effective dose can be an indicator of the magnitude of the associated health risk. Taking into account the age at exposure, which introduces an approximate variation of a factor of three, effective dose can be considered an approximate indicator of the stochastic risk. For most situations of practical radiological protection, this approximation is sufficient to inform judgements and the assessment of possible risks, for example in the medical uses of radiation and communication with patients.

Effective dose continues to be key to practical and effective management of the risk of stochastic effects for the purposes of radiological protection. It provides single values that relate to stochastic risk averaged over all organs and tissues as sites of radiation-induced cancer for both sexes, all ages, and even different populations around the world.

Likewise, detriment is also central to the well-established system of radiological protection. As organ and tissue doses are calculated using dosimetric phantoms of

the human body for males and females of various ages (newborn, 1 year, 5 years, 10 years, 15 years, and 20 years), it is possible to present cancer risks and detriment separately for each sex and for different age groups. It would then be clearer that the inferred risk associated with a given effective dose depends on the age and sex of the exposed individuals. The corollary is that optimisation is applied with a better understanding of possible risks. This evolution towards increased scientific precision and clarity could help facilitate the practical application of appropriate protective measures.

As noted previously, a review of the system of radiological protection is underway, aiming towards development of the next fundamental recommendations of ICRP. Considerations include improvement of the discrimination between tissue reactions and stochastic effects, updating of radiological risk models, and revision of the parameters involved in the construction of radiological damage, based on progress in scientific and health knowledge since *Publication 103* (ICRP, 2007). Several task groups have been established or are being considered on related topics, such as the calculation of detriment, the determination of dose and dose-rate effectiveness factors, and the integration of heritable effects and cardiovascular disease risks. The conclusions of these task groups will form cornerstones of the new recommendations. The present publication is part of this dynamic, considering the ways in which the dose quantities used in the system of radiological protection relate to risks, and are used to prevent or optimise protection against these risks, paving the way for future changes.

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# USE OF DOSE QUANTITIES IN RADIOLOGICAL PROTECTION

ICRP PUBLICATION 147

Approved by the Commission in May 2019

**Abstract**–The central dose quantities used in radiological protection are absorbed dose, equivalent dose, and effective dose. The concept of effective dose was developed by the International Commission on Radiological Protection (ICRP) as a risk-adjusted dosimetric quantity for the management of protection against stochastic effects, principally cancer, enabling comparison of estimated doses with dose limits, dose constraints, and reference levels 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 or low dose rates, and equivalence of external and internal exposures. ICRP *Publication 103* provides detailed explanation of the purpose and use of effective dose and equivalent dose to individual organs and tissues. This publication provides further guidance on the scientific basis for the control of radiation risks using dose quantities, and discusses occupational, public, and medical applications. It is recognised that best estimates of risk to individuals will use organ/tissue doses and specific dose risk models. Although doses incurred at low levels of exposure may be measured or assessed with reasonable accuracy, the associated risks are increasingly uncertain at lower doses. Bearing in mind the uncertainties associated with risk projection to low doses or low dose rates, it is concluded that effective dose may be considered as an approximate indicator of possible risk, recognising also that lifetime cancer risks vary with age at exposure, sex, and population group. A further conclusion is that equivalent dose is not required as a protection quantity. It will be more appropriate for limits for the avoidance of tissue reactions for the skin, hands and feet, and lens of the eye to be set in terms of absorbed dose rather than equivalent dose.



*Keywords*: Absorbed dose; Equivalent dose; Effective dose; Stochastic risks; Tissue reactions; Occupational, public, and medical exposures

# MAIN POINTS

- **The purpose of this publication is to consolidate and expand the explanations provided in *Publication 103* (ICRP, 2007a), but also to clarify the use of dose quantities in relation to risks to health, reaching conclusions that go beyond the advice given in *Publication 103*.**

- **Effective dose and collective effective dose are valuable tools for use in the optimisation of protection against stochastic effects, principally cancer, for occupational and public exposures.**

- **Effective dose is used in medicine for comparing doses from different medical procedures, informing judgements on justification, and establishing constraints for carers and volunteers in medical research. Where doses from the same technique are being compared, measurable quantities are preferred.**

- **Effective dose will generally be used at doses below 100 mSv, but its use at acute doses in the range up to approximately 1 Sv is reasonable, noting the possibility of occurrence of tissue reactions, particularly from non-uniform distribution of dose.**

- **Bearing in mind the uncertainties associated with risk projection to low doses or low dose rates, effective dose may be considered as an approximate indicator of possible risk, recognising that lifetime cancer risks vary with age at exposure, sex, and population group. It is emphasised that use of effective dose in this way is not a substitute for specific risk analysis for individual cancer types using organ/tissue doses.**

- **The use of collective effective dose to predict potential/possible health effects should be treated with caution, put into context, and judged in relation to background morbidity rates.**

- **Absorbed dose is the most appropriate quantity for use in setting limits on organ/tissue doses to prevent tissue reactions (deterministic effects). The Commission expects to change from the use of equivalent dose to set limits on organ/tissue doses at the time that new general recommendations are issued.**

# EXECUTIVE SUMMARY

(a) The dosimetric quantities used in radiological protection are absorbed dose [with the unit of gray (Gy)], equivalent dose, and effective dose [both with the unit of sievert (Sv)]; the base unit is $J\,kg^{-1}$ in each case. Absorbed dose is calculated for protection purposes as an average over organs and tissues, and is the primary scientific quantity from which effective dose is calculated. Absorbed dose is the most appropriate quantity for use in setting limits on organ/tissue doses to prevent tissue reactions (deterministic effects). Equivalent dose is an intermediate quantity in the calculation of effective dose, and the radiation weighting factors ($w_R$) applied to absorbed doses and used in the calculation of equivalent dose relate to stochastic effects at low levels of exposure rather than tissue reactions. The Commission considers that the use of equivalent dose to set limits on organ/tissue doses to prevent tissue reactions should be discontinued, but that current limits can continue to be applied until new general recommendations are issued. Radiation weighting for tissue reactions will require further consideration.

(b) Effective dose is calculated as the weighted average of organ/tissue equivalent doses, summing equivalent doses multiplied by tissue weighting factors ($w_T$) which provide a simplified representation of fractional contributions to total stochastic detriment from cancer and heritable effects. Detriment-adjusted nominal risk coefficients ($Sv^{-1}$) are calculated as averages from sex-, age-, and population-specific values to provide internationally applicable coefficients for all workers (18–64 years of age at exposure) and the whole population (0–84 years of age at exposure). Effective dose 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 risks of cancer and heritable effects. It has proved to be a valuable and robust quantity for use in the optimisation of protection for workers and members of the public, the setting of control criteria (constraints, reference levels, and limits), and the demonstration of compliance. Its use requires the assumption of a linear non-threshold dose–response relationship between dose and risk at low doses or low dose rates, the equivalence of effect of acute and chronic low-level exposures, and the equivalence of effect of internal and external exposures. Although effective dose is most commonly used at doses below 100 mSv, its use in emergency exposure situations at acute doses in the range up to approximately 1 Sv is reasonable. However, it should be noted that in addition to the increased risk of stochastic effects at higher doses, the possibility of occurrence of tissue reactions should also be considered at such doses, particularly if a significant contribution is made by non-uniform distribution of absorbed dose from external sources or from radionuclides concentrated in specific tissues/organs.

(c) Effective dose is calculated for sex-averaged Reference Persons of specified ages. The *Publication 103* (ICRP, 2007a) definition of effective dose includes the specification of Reference Male and Female anatomical models for radiation transport calculations. While exposures may relate to individuals or population groups, effective dose is calculated for Reference Persons exposed in a defined way.

The Commission 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 coefficients 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. Site-specific information on the exposure should be used if available and if the level of exposure warrants more precise estimation of dose.

(d) In evaluating annual exposures, effective dose is calculated as the sum of external dose received in the year and committed dose from internal exposures during the year, where committed dose is integrated over a 50-year period for adults and up to 70 years of age for children. This procedure introduces an element of conservatism for long-lived radionuclides with long biological half-times, but for many radionuclides, all or most of the dose is delivered in the first year after intake. Although effective dose coefficients are provided for a number of paediatric age groups, it is normally sufficient in public dose assessments to consider the age groups of 1 year and 10 years, together with adults. Effective dose coefficients for the fetus following intakes of radionuclides are provided for comparison with dose for other age groups, showing that it is only in the case of a few radionuclides that fetal doses may need to be considered.

(e) While age-, sex-, and population-related differences in risks per Gy are recognised, the use of constraints, reference levels, and limits expressed in effective dose and applied to all workers and all members of the public, together with optimisation, provides a pragmatic, equitable, and workable system of protection that does not distinguish on an individual basis. A distinction should be drawn between the use of scientific information to construct a workable and acceptable protection system and the provision of best scientific estimates of dose and risk to individuals and specific population groups.

(f) In medical applications, estimates of effective dose can be used for comparing doses from different diagnostic and interventional imaging modalities (e.g. computed tomography and nuclear medicine) and exposure techniques that give different spatial distributions of radiation within the body tissues. In this context, effective dose is used to provide a generic indicator for classifying different types of medical procedure into broad risk categories for the purpose of communicating risks to clinicians and patients. Effective dose is also used to inform decisions on justification of patient diagnostic and interventional procedures, planning requirements in research studies, and evaluation of unintended exposures. In each of these cases, effective dose provides an approximate measure of possible detriment. Thus, effective dose can be used prospectively as an indicator of radiation detriment in justification decisions and when planning medical research studies involving radiation exposure, or retrospectively in assessments of accidental exposures. However, measurable quantities are used directly in applications comparing doses from particular procedures in different health centres, including the setting of diagnostic reference levels and in maintenance of patient records.

(g) Bearing in mind the uncertainties associated with risk projection to low doses or low dose rates, effective dose may be considered as an approximate indicator of possible risk, recognising also that lifetime cancer risk varies with age at exposure, sex, and population group. For medical procedures or other situations in which a single organ receives the majority of the dose, such as the breast in mammography or the thyroid from therapeutic administration of radioiodine, mean absorbed doses to the tissues of interest should be used rather than effective dose. In considering doses to patients with diseases with poor prognoses, life expectancy will be a consideration in evaluating radiation risks. The use of effective dose as an approximate indicator of possible risk is not a substitute for a risk analysis using best estimates of organ/tissue doses; appropriate information on the relative effectiveness of different radiation types; and age-, sex-, and population-specific risk factors, with consideration of uncertainties.

(h) Collective effective dose is a valuable tool in the optimisation of protection of workers and the public. It can be used, together with the distribution of individual doses, to inform decisions on the optimum balance between relatively large exposures of a few workers and smaller exposures of a larger number of workers. For public exposures, it can be used as part of the optimisation process for planned, existing, and emergency exposure situations. For occupational, public, and medical exposures, it has been used in comparisons of exposure levels in different countries and changes in dose levels with time (e.g. UNSCEAR, 2008; NCRP, 2019). Its use to predict potential/possible health effects may be useful in particular circumstances – for example, to inform judgements on the need for medical or epidemiological follow-up – but should be treated with caution and judged in relation to background morbidity rates, with consideration of the distribution of doses in time and space, and uncertainties in dose and risk estimation. The computation of numbers of cases of cancer based on collective effective doses involving extremely low exposures to very large populations should be avoided. Due to the large uncertainties associated with such estimates, the results will be more misleading than informative. The Commission has given advice on the use of collective dose as a tool for optimisation of protection in *Publication 101* (ICRP, 2006), taking account of the need to disaggregate doses when necessary to allow separate consideration of homogenous parts of the dose distribution in time and space.

# 1. INTRODUCTION

(1) The system of radiological protection requires dose quantities to set limits to prevent tissue reactions and dose criteria (limits, constraints, reference levels) to optimise protection from stochastic effects. The Commission uses absorbed dose, equivalent dose, and effective dose for these purposes as described in the 2007 Recommendations (ICRP, 2007a). In addition to these quantities, committed dose and collective dose are also used. The Commission provides dose coefficients for circumstances of exposure of workers, members of the public, and patients. The International Commission on Radiation Units and Measurements (ICRU) has defined operational quantities for occupational exposures to external sources that are measurable quantities providing reasonable estimates of the ICRP protection quantities. Detailed guidance on the use of dose quantities in radiological protection is provided in *Publication 103* (ICRP, 2007a). The purpose of this publication is to consolidate and expand the explanations provided previously, but also to clarify the use of dose quantities in relation to risks to health, reaching conclusions that go beyond the advice given in *Publication 103*.

(2) Effective dose was introduced in the 1990 Recommendations (ICRP, 1991a), although the original concept of the use of a single quantity for the control of occupational and public exposures to external and internal sources of radiation dates back to the 1977 Recommendations (ICRP, 1977). Its use has been extended to members of the public of all ages, and in-utero exposures of the fetus (ICRP, 2001, 2003a, 2012b). In addition, it is widely used in medical applications for which the primary requirement is for estimates of detriment, mainly from cancer, for the purpose of understanding the implications of different diagnostic modalities.

(3) The ICRP protection quantities – equivalent dose and effective dose – enable the summation of doses from external sources and from internal emitters to provide a single number for comparison with dose limits, dose constraints, and reference levels that relate to potential stochastic effects of uniform whole-body radiation exposure; that is, risks of developing cancer and of heritable effects. The primary application of effective dose is in the planning of protection, and demonstration of compliance in various situations of exposure of workers and members of the public. The calculation of effective dose can be seen as a three-step process, starting with the mean absorbed dose to organs and tissues [in grays(Gy), $J\,kg^{-1}$]. As radiation types differ in their ability to cause biological effects including cancer, the second step is to multiply the calculated values of absorbed dose by radiation weighting factors that take account of the greater effectiveness of densely ionising radiations, including alpha particles and neutrons, compared with sparsely ionising beta particles and gamma rays. The result is termed 'equivalent dose' [in sieverts (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. Thus, effective dose is a doubly weighted average of organ/tissue absorbed doses. The intention is that the overall risk per Sv should be comparable irrespective of the type and distribution of radiation exposure; effective

dose, expressed in Sv, is the well-known quantity in radiological protection that is often referred to simply as 'dose'.

(4) *Publication 103* (ICRP, 2007a) provided detailed explanation of the purpose and use of the ICRP protection quantities. However, experience has shown the need for further clarification and guidance, with identified issues including the following:

- Confusion between equivalent dose and effective dose expressed in the same units (Sv) when they are not distinguished carefully, particularly when considering doses from internal emitters that concentrate in specific organs, such as $^{131}$I (Gonzalez et al., 2013) (see Section 3.3, Para. 42).
- The use of equivalent dose in setting limits for the avoidance of tissue reactions in the cases of irradiation of 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, with different limits for workers and members of the public (see Section 2.2).
- Confusion between operational quantities used to measure exposures to external sources and the protection quantities: 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) (see Sections 2.2, 3.3, and 3.8).
- Apparent inconsistencies in the setting of radiation weighting factors, with a simple approach for all low-linear energy transfer (LET) radiations and alpha particles but greater complexity for neutrons, and the use of a different weighting approach using quality factor for the operational quantities (see Section 3.3).
- The use of a single set of tissue weighting factors in the calculation of effective dose for all age groups and both sexes, despite recognised age-, sex-, and population-related differences in cancer risks (see Sections 2.5, 3.4, and 4.2, Para. 81).
- The calculation of effective dose for a sex-averaged Reference Person rather than separately for males and females, and for children as well as adults, and confusion between Reference Person and Representative Person (see Sections 3.6 and 4.2, Paras 79, 80).
- The dose range over which effective dose is applicable, particularly in considering higher exposures that may occur in accidents that may involve high absorbed doses to individual organs/tissues (see Section 3.4).
- The apparent conservatism of calculating committed dose from internal emitters; that is, dose integrated over a 50-year period for adults and to 70 years of age for children (ICRP, 2007a) (see Section 3.5).
- The calculation of effective dose to the fetus following maternal exposures to internal emitters (see Sections 3.6 and 4.2).
- The use of effective dose to estimate risks, particularly in evaluating exposures of patients from medical procedures (see Section 5).
- The use of collective effective dose to evaluate risks to population groups (see Section 3.7).

(5) Section 2 of this publication summarises information on tissue reactions and stochastic effects resulting from radiation exposures, updating *Publication 103* (ICRP, 2007a); explains the methodology adopted to derive detriment-adjusted nominal risk coefficients and the tissue weighting factors used in the calculation of effective dose; and provides more information than presented in *Publication 103* on variations in estimates of lifetime excess cancer risk with age at exposure and between sexes. Section 3 presents and discusses absorbed dose, equivalent dose, and effective dose, and also discusses committed and collective dose, and the ICRU operational quantities. Section 4 considers the application of dose quantities in the evaluation and control of exposures of workers and members of the public in planned, existing, and emergency exposure situations. Section 5 examines the use of dose quantities in medicine, and the use of effective dose as an approximate indicator of possible risk.

# 2. HEALTH EFFECTS AND DETRIMENT

## 2.1. Categories of radiation effects

(6) *Publication 103* (ICRP, 2007a) provides detailed explanations of the judgements made, and approaches taken, regarding the quantification of radiation risks for radiological protection purposes. A distinction has been made between two major classes of health effects:

- Tissue reactions (deterministic effects – impairment of organ/tissue function occurring above dose thresholds, with severity increasing with increasing dose.
- Stochastic effects (cancers and heritable diseases – predominantly the risk of cancer occurring in exposed populations, with increasing frequency (but not severity) with increasing dose, and assuming that there is no threshold below which there is no risk.

## 2.2. Tissue reactions (deterministic effects)

(7) *Publication 103* (ICRP, 2007a) made no changes to previously recommended annual dose limits for tissue reactions in relation to planned exposure situations, set in terms of equivalent dose, of 150 mSv 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 (Neriishi et al., 2007; Worgul et al., 2007). *Publication 118* (ICRP, 2012a) provided a comprehensive review and analysis of tissue reactions caused by radiation that confirmed the judgements made in *Publication 103* (Annex A) regarding threshold doses in most cases. However, more recent epidemiological data reviewed in *Publication 118* suggested a lower threshold for induction of lens opacities of approximately 0.5 Gy compared with the values given in *Publication 103* 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 approximately 0.5 Gy (ICRP, 2012a; Bouffler et al., 2015). In response to this evidence, the Commission (ICRP, 2012a) issued a statement on tissue reactions recommending that the annual limit on equivalent dose to the lens of the eye for occupational exposures should be reduced to 20 mSv, averaged over 5 years with dose in any year not exceeding 50 mSv.

(8) Judgements on the risks of cataract are based largely on epidemiological studies of the effects of external exposures to gamma rays (Ainsbury et al., 2009; ICRP, 2012a). In general, there is limited information available that can be used to compare the effectiveness of radiations of different qualities in causing tissue reactions (Hamada and Sato, 2016). However, the available data indicate that differences

between radiation types (e.g. alpha particles and neutrons relative to gamma rays) in their effectiveness per Gy in causing tissue reactions are smaller than differences in their effectiveness in relation to cancer induction (ICRP, 1990, 2003b).

(9) The Commission considers that instead of using equivalent dose to set limits to prevent tissue reactions, the more appropriate quantity is absorbed dose. This change will draw a clear distinction between limits applying to tissue reactions, set in absorbed dose (Gy), and those applying to stochastic effects, set in effective dose (Sv). The Commission expects to introduce this change at the time of its next general recommendations. The limits for the lens of the eye (cataract), skin, and hands and feet are relevant mainly to circumstances of exposure to penetrating low-LET radiations. However, exposures to neutrons and other high-LET radiations may require consideration in some situations, and it may then be necessary to take account of increased effectiveness per Gy compared with low-LET radiation. Consideration will therefore be given to radiation weighting for tissue reactions (see also Section 3.3). The anticipated change is consistent with the approach taken by the US National Council on Radiation Protection and Measurements (NCRP, 2018) and proposals from ICRU for changes to operational quantities (Sections 3.3 and 3.8).

(10) *Publication 118* (ICRP, 2012a) concluded that a threshold dose as low as 0.5 Gy may apply to circulatory diseases; that is, cardiovascular and cerebrovascular diseases caused by doses delivered to the heart and brain, and associated tissues. The statement on tissue reactions (ICRP, 2012a) drew attention to the need for medical practitioners to be aware, as patient doses 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 or low dose rates of a similar magnitude to those inferred for cancer detriment at low doses or low dose rates (Little, 2016). However, the National Council on Radiation Protection and Measurement (NCRP) (2018) concluded from a review of human studies that there is insufficient evidence that absorbed doses $\leq$0.5 Gy to the heart cause cardiovascular diseases (NCRP, 2018). The Commission will continue to review scientific developments that inform judgements on whether circulatory disease should be included as a component of low dose or low dose rate detriment, but further mechanistic understanding is required to determine whether stochastic processes are involved in the development of radiation-induced circulatory disease (Hendry, 2015).

## 2.3. Stochastic effects (cancers and heritable diseases)

(11) 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; UNSCEAR, 2008; NCRP, 2018). In general, the epidemiological data show a linear dose–response relationship between cancer rates and absorbed dose from gamma rays from approximately

100 mGy to a few Gy. Attempts are being made to extend observations to lower doses or lower dose rates, notably studies on large worker cohorts (Muirhead et al., 2009; Leuraud et al., 2015; Richardson et al., 2015, 2018; Sokolnikov et al., 2015; Kuznetsova et al., 2016; Haylock et al., 2018) and studies of children receiving computed tomography (CT) scans (Pearce et al., 2012; Mathews et al., 2013; Huang et al., 2014; Journy et al., 2015; Berrington de Gonzalez et al., 2016; Meulepas et al., 2019). The CT studies reported some statistically significant elevation of cancer rates at doses of a few tens of mSv. However, caution has been advised in the interpretation of these studies (Walsh et al., 2013, 2014; 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 undetected cancers that prompted their CT examinations (an example of reverse causation), or factors that predispose to cancer may have led to medical conditions that require CT scans (an example of confounding by indication) (UNSCEAR, 2013; Walsh et al., 2013, 2014; Boice, 2015).

(12) A number of assumptions and judgements are made in quantifying low dose or low dose rate cancer risks (ICRP, 2007a). Based on epidemiological analyses from the 1990s, a dose and dose rate effectiveness factor (DDREF) of 2 was applied to the solid cancer risks derived from the atomic bomb survivor studies. Currently, epidemiology provides limited evidence of a DDREF $>1$ for solid cancer in humans, although analyses continue (Rühm et al., 2016; Shore et al., 2017), but animal and in-vitro data indicate curvilinear dose–response relationships that provide some support for the use of a DDREF $>1$. As discussed in *Publication 131* (ICRP, 2015c), the component factors, dose effectiveness factor and dose-rate effectiveness factor, may be considered to be mechanistically distinct, with the former applying to low acute doses, and the latter applying to protracted doses for which long-term kinetics of target stem cells may modify responses. For leukaemia, the atomic bomb survivor data are consistent with the use of a linear-quadratic dose–response relationship, with the dose–response being linear at doses $<0.1$ Gy. Having obtained cancer risk estimates for exposures at low doses of a few tens of mGy, an LNT dose–response relationship is assumed. This LNT dose–response assumption is considered to represent a prudent interpretation of current evidence including mechanistic understanding of radiation-induced cancer at low doses or low dose rates (Preston et al., 2003, 2007; ICRP, 2007a; UNSCEAR, 2012b). In a review of all relevant epidemiological studies, NCRP (2018) concluded that current epidemiological data support the continued use of the LNT dose–response relationship for radiological protection purposes, with no other model representing a more pragmatic or prudent interpretation.

(13) 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 becomes increasingly uncertain as dose decreases.

(14) *Publication 103* (ICRP, 2007a) notes that there is no reliable direct evidence from human epidemiological studies of deleterious heritable effects of radiation, but considers the inclusion of heritable risk in overall stochastic risks to be a prudent interpretation of evidence of heritable effects in experimental animals. Following a detailed analysis by UNSCEAR (2001) and ICRP (2007a), estimates of heritable risk over two generations have been applied in calculations of radiation detriment.

## 2.4. Nominal risk coefficients and detriment

(15) Annex A of *Publication 103* (ICRP, 2007a) explains the methodology applied to calculate nominal risk coefficients for radiation-induced stochastic health effects and associated values of detriment. Detriment is a concept used to quantify the harmful effects on health of radiation exposures at low doses or low dose rates, taking account of the severity of disease in terms of lethality, quality of life, and years of life lost. The steps in the calculation are outlined in Annex A of *Publication 103* and summarised here. The Commission is preparing a separate report that examines the calculation of detriment, and considers sensitivity to assumptions made in the calculations.

(16) Largely using analyses of follow-up data on the Japanese atomic bomb survivors, male and female lifetime excess cancer risks were estimated for 14 organs or tissues, using both excess relative risk (ERR) and excess absolute risk (EAR) models. Lifetime risk estimates were adjusted downward by a factor of 2 to account for a DDREF, except for leukaemia, for which a linear-quadratic model for risk was used. For each specified organ or tissue, a weighting of the ERR and EAR lifetime risk estimates was established based on judgments on the relative applicability of the two models; for example, ERR:EAR weights of 0:100% were assigned for breast, 100:0% for thyroid, 30:70% for lung, and 50:50% for other cancers. The resulting risk estimates were averaged across selected Asian and Euro-American populations, and between sexes to provide the nominal risk coefficients given in Table 2.1. The Asian population is a composite of the populations covered by the cancer registries for China (Shanghai) and Japan (Osaka, Hiroshima, and Nagasaki), and the Euro-American population is a composite of the populations of cancer registries from Sweden, the UK, and the USA (Surveillance, Epidemiology, and End Results Program).

(17) Lifetime excess risks of cancer incidence were adjusted for fatality by multiplying by lethality fractions derived from cancer survival data. A further adjustment was applied to account for the morbidity and suffering associated with non-fatal cancers. As cancer types differ in their age at onset and the consequent number of years of life lost, a weighting factor was applied to adjust for this difference. The cancer detriment values resulting from these calculations and estimated risks of heritable effects from irradiation of the gonads are shown in Table 2.1. The forthcoming report on detriment calculations will provide further details, clarifying the description given in *Publication 103* (ICRP, 2007a).

Table 2.1. Summary of *Publication 103* (ICRP, 2007a) nominal cancer risks and detriment for uniform whole-body exposure to gamma rays (from Table A.4.1, *Publication 103*, Annex A).

| Tissue | Nominal risk coefficient (cases per 10,000 persons per Gy)* | Lethality fraction | Nominal risk adjusted for lethality and quality of life | Relative cancer-free life lost | Detriment (relating to column 1) | Relative detriment† |
|---|---|---|---|---|---|---|
| (a) Whole population (0–84 years of age at exposure) | | | | | | |
| 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 | 0.007 |
| Breast | 112 | 0.29 | 61.9 | 1.29 | 79.8 | 0.139 |
| Ovary | 11 | 0.57 | 8.8 | 1.12 | 9.9 | 0.017 |
| Bladder | 43 | 0.29 | 23.5 | 0.71 | 16.7 | 0.029 |
| Thyroid | 33 | 0.07 | 9.8 | 1.29 | 12.7 | 0.022 |
| 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 (heritable) | 20 | 0.80 | 19.3 | 1.32 | 25.4 | 0.044 |
| Total | 1715 | | 565 | | 574 | 1.000 |
| (b) Working population (18–64 years of age at exposure) | | | | | | |
| 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 (heritable) | 12 | 0.80 | 12 | 1.32 | 15.3 | 0.036 |
| Total | 1179 | | 423 | | 422 | 1.000 |

*Risk coefficients are cases per 10,000 persons per Gy absorbed dose from uniform whole-body gamma ray exposures.

†The values given should not be taken to imply undue precision but are presented to three significant figures to facilitate the traceability of the calculations made and choice of tissue weighting factors.

(18) Table 2.2 summarises the detriment-adjusted risk coefficients derived in *Publication 103* (ICRP, 2007a) and compares them with the values used in *Publication 60* (ICRP, 1991a).

Table 2.2. Detriment-adjusted nominal risk coefficients per effective dose ($10^{-2}$ $Sv^{-1}$) (ICRP, 1991a, 2007a).

| | Cancer | | Heritable effects | | Total | |
|---|---|---|---|---|---|---|
| Exposed population | *Publication 103* | *Publication 60* | *Publication 103* | *Publication 60* | *Publication 103* | *Publication 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 |

*Working population (18–64 years of age at exposure).

(19) The *Publication 103* (ICRP, 2007a) values for cancer risks are based on considerably improved epidemiological analyses and use of incidence rather than mortality data. The lower values for heritable effects are considered a more scientifically robust interpretation of the available experimental data and evidence on human heritable disease. While the cancer risk data used to derive the nominal risk coefficients relate almost exclusively to external exposures to gamma rays, the overall population values are expressed in effective dose (Sv) and taken to apply to all radiation exposures (see Sections 2.7 and 3).

## 2.5. Tissue weighting factors

(20) Table 2.3 shows the tissue weighting factors, based on the relative detriment values shown in Table 2.1, as used in *Publication 103* (ICRP, 2007a) in the calculation of effective dose. As outlined in Section 1 and explained further in Section 3, effective dose is calculated as the weighted mean of equivalent doses to individual organs and tissues, using tissue weighting factors to represent contributions to total

Table 2.3. *Publication 103* (ICRP, 2007a) 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 region, gallbladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, and uterus/cervix.

detriment. The intention of this procedure is that the overall risk per unit effective dose will approximate the values shown in Table 2.2, irrespective of the contributions made by doses to individual organs and tissues. Due to the uncertainties associated with the calculations of the nominal risk coefficients and detriment values shown in Table 2.1, and their application to low dose or low dose rate exposures to external and internal sources, the tissue weighting factors shown in Table 2.3 are simplified and rounded to avoid any spurious impression of accuracy. Furthermore, 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 in the exposed individual and heritable effects. A tissue weighting factor of 0.01 was applied to salivary glands and brain despite risks not being specifically quantifiable, as it was judged that they may be more sensitive to radiation-induced cancer than other tissues constituting the 'remainder' group.

## 2.6. Age- and sex-specific cancer risks

(21) The nominal risk and detriment coefficients provided in *Publication 103* (ICRP, 2007a) are age-, sex-, and population-averaged values, but with the distinction between the whole population (0–84 years of age at exposure) and the working population (18–64 years of age at exposure). Risks for the general population are somewhat larger because risks are generally greater for exposures at younger ages.

(22) Wall et al. (2011) examined the variation of lifetime excess cancer risk with cancer type, sex, and age at exposure. Their methodology was slightly different from that used in *Publication 103* (ICRP, 2007a), but their results illustrated variations of nominal risks with age and sex. The cumulative risk of cancer incidence per unit organ/tissue absorbed dose (Gy) up to an attained age of 100 years was calculated separately for males and females, and by category of age at exposure (10 age categories of 10 years, from 0–9 years to 90–99 years), for 11 different cancer types (female breast, lung, stomach, colon, bladder, liver, thyroid, oesophagus, ovary, leukaemia, and other solid cancer sites). Risk models were derived from the atomic bomb survivor cohort (Preston et al., 2007) using *Publication 103* methodology. To define baseline incidence rates, Wall et al. (2011) used *Publication 103* values for a Euro-American composite population. The values in Table 2.4 are calculated as lifetime attributable risk rather than risk of exposure-induced cancer as in Wall et al. (2011), but the results are similar.

(23) Table 2.5 shows results of identical calculations but with baseline incidence rates from the ICRP Asian composite populations. Comparison of these data shows the same pattern in both populations, with overall risks compared with those in the age 30–39 years at exposure group being approximately double in the youngest group (0–9 years at exposure) and approximately half for age 60–69 years at exposure. However, the data also show substantial differences between cancer types, as illustrated in Fig. 2.1 for lung and thyroid cancer, with some differences between the two composite populations in the age-at-exposure dependence of risk for individual

Table 2.4. Estimates of lifetime attributable risks of cancer incidence per absorbed dose (cases per 100 per Gy) from uniform external exposure to gamma rays for the ICRP Euro-American composite population (ICRP, 2007a).

| | Age at exposure (years) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Organ | 0–9 | 10–19 | 20–29 | 30–39 | 40–49 | 50–59 | 60–69 | 70–79 | 80–89 | 90–99 |
| *Males* | | | | | | | | | | |
| Lung | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.6 | 0.4 | 0.2 | 0.03 |
| Stomach | 1.0 | 0.8 | 0.6 | 0.4 | 0.3 | 0.2 | 0.1 | 0.05 | 0.02 | 0.0 |
| Colon | 1.6 | 1.3 | 1.1 | 0.8 | 0.6 | 0.4 | 0.2 | 0.1 | 0.04 | 0.0 |
| RBM | 1.3 | 1.3 | 0.8 | 0.7 | 0.7 | 0.4 | 0.3 | 0.1 | 0.07 | 0.02 |
| Bladder | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.3 | 0.2 | 0.1 | 0.05 | 0.01 |
| Liver | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 | 0.06 | 0.03 | 0.01 | 0.0 |
| Thyroid | 0.4 | 0.2 | 0.06 | 0.03 | 0.01 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Oesophagus | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.08 | 0.05 | 0.01 |
| Other | 4.9 | 3.2 | 2.4 | 1.4 | 0.9 | 0.5 | 0.3 | 0.1 | 0.03 | 0.0 |
| All cancers | 11.5 | 8.8 | 6.8 | 5.0 | 4.0 | 2.9 | 1.9 | 1.0 | 0.4 | 0.08 |
| *Females* | | | | | | | | | | |
| Breast | 6.7 | 4.1 | 2.5 | 1.5 | 0.8 | 0.4 | 0.2 | 0.07 | 0.02 | 0.0 |
| Lung | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 1.9 | 1.6 | 1.1 | 0.5 | 0.06 |
| Stomach | 1.7 | 1.3 | 1.0 | 0.7 | 0.5 | 0.3 | 0.2 | 0.1 | 0.05 | 0.0 |
| Colon | 0.8 | 0.7 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 | 0.08 | 0.03 | 0.0 |
| RBM | 0.5 | 0.5 | 0.5 | 0.4 | 0.5 | 0.3 | 0.2 | 0.1 | 0.04 | 0.01 |
| Bladder | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.4 | 0.3 | 0.2 | 0.1 | 0.01 |
| Liver | 0.3 | 0.2 | 0.2 | 0.1 | 0.09 | 0.06 | 0.04 | 0.02 | 0.01 | 0.0 |
| Thyroid | 1.9 | 0.8 | 0.3 | 0.1 | 0.04 | 0.01 | 0.0 | 0.0 | 0.0 | 0.0 |
| Oesophagus | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.03 |
| Ovary | 0.6 | 0.4 | 0.3 | 0.2 | 0.2 | 0.1 | 0.06 | 0.03 | 0.01 | 0.0 |
| Other | 3.7 | 2.5 | 1.7 | 1.2 | 0.8 | 0.5 | 0.3 | 0.1 | 0.05 | 0.0 |
| All cancers | 18.5 | 13.0 | 9.4 | 7.1 | 5.7 | 4.4 | 3.2 | 2.1 | 1.0 | 0.1 |

RBM, red bone marrow.

Risks are calculated using excess absolute risk (EAR) and excess relative risk (ERR) models and applying a dose and dose rate effectiveness factor of 2 for all cancer types other than leukaemia (ERR:EAR of 100:0% for thyroid, 30:70% for lung, 0:100% for breast, 50:50% for all others). The model of Preston et al. (2002) was used for breast cancer. Minimum latency periods applied were 2 years for leukaemia and 5 years for solid cancers.

Table 2.5. Estimates of lifetime attributable risks of cancer incidence per absorbed dose (cases per 100 per Gy) from uniform external exposure to gamma rays for the ICRP Asian composite population (ICRP, 2007a).

| | Age at exposure (years) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Organ | 0–9 | 10–19 | 20–29 | 30–39 | 40–49 | 50–59 | 60–69 | 70–79 | 80–89 | 90–99 |
| *Males* | | | | | | | | | | |
| Lung | 0.7 | 0.8 | 0.8 | 0.8 | 0.9 | 0.8 | 0.7 | 0.4 | 0.2 | 0.04 |
| Stomach | 1.6 | 1.3 | 1.0 | 0.8 | 0.6 | 0.4 | 0.2 | 0.1 | 0.03 | 0.0 |
| Colon | 1.9 | 1.5 | 1.2 | 0.9 | 0.7 | 0.5 | 0.3 | 0.1 | 0.04 | 0.01 |
| RBM | 1.3 | 1.3 | 0.8 | 0.7 | 0.7 | 0.5 | 0.3 | 0.1 | 0.07 | 0.02 |
| Bladder | 0.5 | 0.5 | 0.4 | 0.3 | 0.3 | 0.2 | 0.2 | 0.09 | 0.04 | 0.01 |
| Liver | 1.1 | 0.8 | 0.7 | 0.5 | 0.4 | 0.2 | 0.1 | 0.05 | 0.01 | 0.0 |
| Thyroid | 0.3 | 0.1 | 0.06 | 0.02 | 0.01 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Oesophagus | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.09 | 0.06 | 0.01 |
| Other | 2.9 | 1.9 | 1.3 | 0.9 | 0.6 | 0.3 | 0.2 | 0.07 | 0.02 | 0.0 |
| All cancers | 10.5 | 8.3 | 6.4 | 5.1 | 4.1 | 3.0 | 2.0 | 1.1 | 0.5 | 0.09 |
| *Females* | | | | | | | | | | |
| Breast | 6.8 | 4.1 | 2.5 | 1.5 | 0.8 | 0.4 | 0.2 | 0.06 | 0.02 | 0.0 |
| Lung | 1.4 | 1.4 | 1.5 | 1.6 | 1.7 | 1.6 | 1.4 | 0.9 | 0.5 | 0.09 |
| Stomach | 2.2 | 1.7 | 1.3 | 1.0 | 0.7 | 0.5 | 0.3 | 0.1 | 0.05 | 0.01 |
| Colon | 0.8 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 | 0.06 | 0.02 | 0.0 |
| RBM | 0.5 | 0.5 | 0.5 | 0.1 | 0.5 | 0.3 | 0.2 | 0.09 | 0.04 | 0.01 |
| Bladder | 0.5 | 0.5 | 0.4 | 0.3 | 0.3 | 0.3 | 0.2 | 0.1 | 0.07 | 0.01 |
| Liver | 0.5 | 0.4 | 0.3 | 0.3 | 0.2 | 0.1 | 0.08 | 0.04 | 0.01 | 0.0 |
| Thyroid | 2.5 | 1.0 | 0.5 | 0.2 | 0.06 | 0.02 | 0.01 | 0.0 | 0.0 | 0.0 |
| Oesophagus | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 | 0.03 |
| Ovary | 0.4 | 0.3 | 0.2 | 0.2 | 0.1 | 0.07 | 0.04 | 0.02 | 0.01 | 0.0 |
| Other | 3.0 | 2.1 | 1.5 | 1.0 | 0.7 | 0.4 | 0.2 | 0.1 | 0.04 | 0.01 |
| All cancers | 18.8 | 12.8 | 9.4 | 6.6 | 5.5 | 4.1 | 2.9 | 1.8 | 0.9 | 0.2 |

RBM, red bone marrow.

Risks are calculated using excess absolute risk (EAR) and excess relative risk (ERR) models and applying a dose and dose rate effectiveness factor of 2 for all cancer types other than leukaemia (ERR:EAR of 100:0% for thyroid, 30:70% for lung, 0:100% for breast, 50:50% for all others). The model of Preston et al. (2002) was used for breast cancer. Minimum latency periods applied were 2 years for leukaemia and 5 years for solid cancers.

cancers. The contribution of the different cancer types to overall lifetime risk varies substantially with sex and age at exposure. Note that variations with age at exposure reflect cumulative lifetime risk of cancer incidence, so reduction of risk with increasing age at exposure reflects mainly the reduction in remaining life time after exposure rather than a variation of sensitivity with age at exposure. It should be recognised that the values given in Tables 2.4 and 2.5 are the results of modelling, based on a set of assumptions that are all subject to uncertainties. However, while it is important to recognise the considerable uncertainties associated with low dose or low dose rate risk estimates (NCRP, 2012; UNSCEAR, 2012b), the overall conclusions regarding age-at-exposure-related changes in risk remain valid, with differences between individual cancers. Estimates of age and sex differences in cancer risks in a Japanese population, calculated using ICRP methodology, were presented by Ogino et al. (2016).

(24) With regard to risks of in-utero irradiation of the fetus, *Publication 103* (1CRP, 2007a) refers to *Publication 90* (ICRP, 2003a). The overall conclusion from the limited available data is that it is reasonable to assume that the overall lifetime excess risk of cancer from in-utero irradiation is, at most, a few times that of the population as a whole, and the risk from exposures in-utero is judged to be no greater than that following exposures in early childhood.

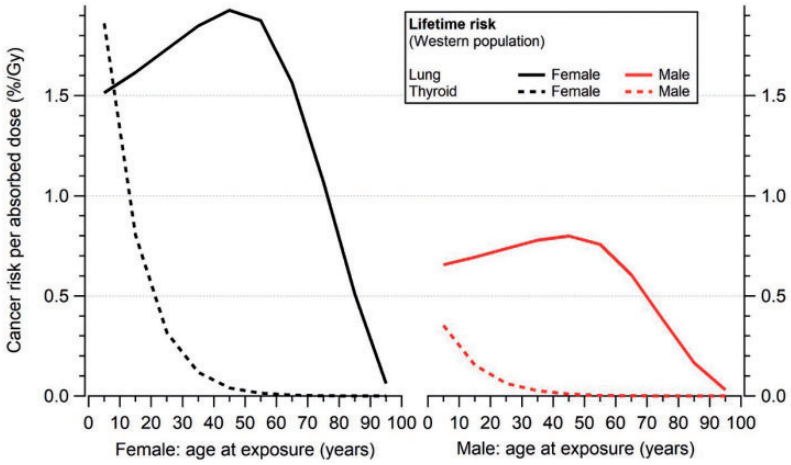


Fig. 2.1. Lifetime attributable risks of cancer incidence per absorbed dose (cases per 100 per Gy; %/Gy) by sex and age at exposure, for uniform external exposure to gamma rays for the ICRP Euro-American composite population (ICRP, 2007a) for lung and thyroid cancer (from Table 2.4).

(25) Nominal risk coefficients and detriment values are averaged over sex and age at exposure within the public and worker populations. Tissue weighting factors are chosen as simplified and rounded values relating to age- and sex-averaged relative detriment values (Table 2.1a). However, it is important for the purposes of this publication to understand potential differences in risk to different population groups and individuals. Particularly in medical applications, but also in other applications, there are situations in which there is a requirement for some understanding of risks associated with particular procedures, and better information may be required than that conveyed by nominal risk coefficients.

(26) In addition to age-at-exposure- and sex-related differences in cancer risk, there are variations in radiation sensitivity between individuals related to genetic and, potentially, environmental/lifestyle differences that are generally not well understood (ICRP, 2007a; AGIR, 2013; Bouffler, 2016). There are 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 cancer risk.

(27) For the practical implementation 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. In applying the system, the underlying differences illustrated in this section should be borne in mind in the context of uncertainties associated with the derivation of risk estimates and their application, particularly at low doses or low dose rates [see NCRP (2012) and UNSCEAR (2012b) for discussion of uncertainties in risk estimates].

## 2.7. Risks from alpha-particle-emitting radionuclides

(28) 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 atomic bomb survivors (bone and skin cancers are exceptions; ICRP, 2007a). An important question for the implementation of the protection system is the extent to which risk factors derived principally from studies of short-term exposures to penetrating external radiation also apply 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.

(29) Harrison and Muirhead (2003) compared risk estimates for radiation-induced cancer derived for exposures to alpha-emitting radionuclides and those derived for the atomic bomb survivors. They considered lung cancer induction by $^{222}$Rn and its progeny, and by $^{239}$Pu; liver cancer induction by Thorotrast (contrast medium containing $^{232}$Th); and bone cancer induction by radium isotopes. They showed that, taking account of the greater effectiveness of alpha particles compared with gamma

rays by up to a factor of approximately 20, the human data show consistency between estimates of radiation risk from these internal emitters and external radiation. Similar conclusions were reached by Little et al. (2007) in an analysis of epidemiological data for internal emitters in comparison with atomic bomb survivor data. Marsh et al. (2014) compared lung cancer risks per Gy from inhaled $^{222}$Rn progeny and $^{239}$Pu, focusing on French uranium miners (Rage et al., 2012) and Mayak workers. While the alpha particle dose from radon progeny is delivered predominantly in the airways, with only a small proportion delivered to the alveolar regions of the lungs, the opposite is the case for alpha particle decay of $^{239}$Pu. Marsh et al. (2014) compared the published values of ERR for lung cancer from these studies, and also calculated values of lifetime excess absolute risk (LEAR), comparing results with values based on the atomic bomb survivor data. Both published values of ERR and calculated values of LEAR showed similar values for $^{222}$Rn progeny and $^{239}$Pu, consistent with central relative biological effectiveness (RBE) values of approximately 10–20 in each case.

(30) Support is also provided by animal and in-vitro data comparing the effects of exposures from different radionuclides and external radiation (UNSCEAR, 2000, 2008; WHO, 2001). However, uncertainties in the dose estimates for internal emitters and the risk estimates should be recognised.

(31) In the case of bone cancer, the atomic bomb survivor data were less informative in the 1990s than epidemiological studies of the effects of internally deposited $^{224}$Ra used medically. The risk coefficient for bone cancer in Table 2.1 was based on *Publication 60* (ICRP, 1991a) considerations of the $^{224}$Ra data. In this case, the risk per Gy was divided by an assumed value for the RBE of alpha particles compared with gamma rays of 20 to obtain an estimate of risk per Gy of low-LET radiation.

(32) It can be concluded that the available epidemiological data, supported by animal and other experimental data, indicate that it is reasonable for protection purposes to assume equivalence of risk per Gy between external gamma rays and internal alpha particle irradiation, when simple adjustments are made to account for RBE. An ICRP report in preparation will provide detailed comparisons of lung cancer risk from $^{222}$Rn progeny, $^{239}$Pu, and external gamma rays.

# 3. DOSE QUANTITIES

## 3.1. Requirements for protection quantities

(33) Dose quantities are required to set limits to prevent tissue reactions and protection criteria (limits, constraints, reference levels) to optimise protection from stochastic effects. The Commission uses absorbed dose, equivalent dose, and effective dose for these purposes as described in Sections 3.2–3.4. As intakes of radionuclides can result in protracted doses delivered over many years, the Commission has defined the concept of committed dose (Section 3.5). The Commission publishes dose coefficients (Sv per exposure/intake) for use in dose assessments (Section 3.6). A further tool defined for the purposes of optimisation of protection is collective dose (Section 3.7). ICRU has defined operational quantities for occupational exposures to external sources that are measurable quantities providing reasonable estimates of the ICRP protection quantities (Section 3.8).

## 3.2. Absorbed dose

(34) Absorbed dose is the basic physical dose quantity used for all types of ionising radiation. The SI unit of absorbed dose is the gray (Gy), where $1\,\mathrm{Gy} = 1\,\mathrm{J\,kg^{-1}}$ in SI base units. Absorbed dose is a measurable quantity, and primary standards exist to determine its value. When using absorbed dose in radiological protection, doses are averaged over tissue volumes. It is assumed that at low doses or low dose rates, 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/mass 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).

## 3.3. Equivalent dose

(35) The definition of equivalent dose is based on the average absorbed dose, $D_{\mathrm{T,R}}$, due to radiations of type $R$ in the volume of a specified organ or tissue $T$. The radiation types $R$ are given by the type and energy of radiation either incident on the body or emitted by radionuclides residing within it. Equivalent dose in an organ or tissue, $H_{\mathrm{T}}$, is then defined by:

$$H_{\mathrm{T}} = \sum_{R} w_{\mathrm{R}} D_{\mathrm{T,R}} \tag{3.1}$$

where $w_R$ is the radiation weighting factor for radiation type $R$. The sum is performed over all types of radiations involved. The SI unit of equivalent dose is the sievert (Sv), where $1\,Sv = 1\,J\,kg^{-1}$ in SI base units.

(36) Radiation weighting in the definition of radiological protection quantities was originally related to the radiation quality factor, $Q$, as a function of LET and denoted as $L$ in the $Q(L)$ function of *Publication 26* (ICRP, 1977). In *Publication 60* (ICRP, 1991a), the method of radiation weighting was changed, with the selection of a set of radiation weighting factors ($w_R$) related to stochastic effects, mainly cancer. The values of $w_R$ were selected largely on the basis of measurements of RBE of the different radiations for a range of biological endpoints related to stochastic effects. RBE values are experimentally determined, where the RBE is the ratio of the absorbed dose of a test radiation and a low-LET reference radiation that produces the same level of observed effect (ICRP, 2003b). A range of RBE values are observed depending on the biological endpoint studied and also on the reference radiation; common reference radiations are megavoltage x rays or $^{60}Co$ gamma radiation. Judgements concerning $w_R$ values are based on maximum RBE values ($RBE_{max}$) corresponding to low doses or low dose rates of the reference low-LET radiation (ICRP, 2003b). Table 3.1 shows the $w_R$ values adopted in *Publication 103* (ICRP, 2007a).

(37) The use of a $w_R$ of 1 for all emissions of photons, electrons, and muons is not intended to imply that there are no differences in biological effectiveness at different energies. This simple approach is considered sufficient for the intended applications of effective dose. For retrospective risk assessments, more detailed information on the radiation field and appropriate RBE values may need to be considered if relevant data are available, but such considerations go beyond the intended applications of effective dose. Heterogeneity of the radiation dose within cells, as can occur with Auger emitters incorporated into DNA, for example, may also require specific analysis in risk assessments.

(38) The radiation weighting factor for neutrons reflects the RBE of neutrons following external exposure. The biological effectiveness of neutrons incident on

Table 3.1. *Publication 103* (ICRP, 2007a) 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. 3.1) |

All values relate to the radiation entering body tissues.

the human body is strongly dependent on neutron energy (see ICRP, 2007a, Annex B). The energy function shown in Fig. 3.1 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 $>50$ MeV as, for physical reasons, RBE values are assumed to converge with those for protons.

(39) 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 $>10$ 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.

(40) 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 depending on the organ/tissue and cancer type being considered. The distribution of radionuclides in organs and tissues and the estimation of dose is complex and associated with substantial uncertainties, contributing to observations of a broad range of RBE values (see Section 2.7; ICRP, 2003b, 2007a). A single $w_R$ value of 20 is used for alpha particle irradiation, and the same value is used for fission fragments and as a conservative value for heavy ions.

(41) It has been argued [e.g. Thomas and Edwards (2003)] that the Commission's treatment of radiation weighting for the calculation of effective dose exhibits inconsistencies, is unnecessarily complex, and over-interprets the available biological data.

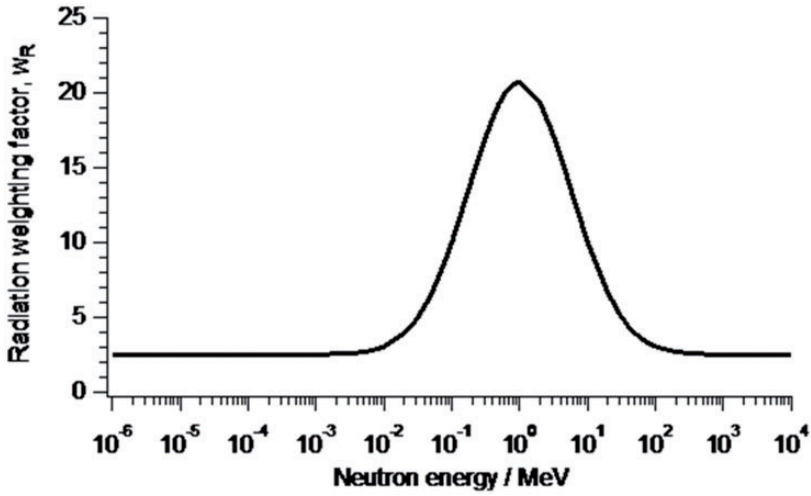


Fig. 3.1. Energy function for radiation weighting factor for neutrons.

It was suggested that, for protection purposes, it would be 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 simplified 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 and estimation of risk to astronauts, which can be substantial and involves consideration of exposures to complex radiation fields (ICRP, 2013). The Commission is aware of these proposals and, while no changes to current methodology are considered necessary, this topic will be within the scope of review for the next general recommendations.

(42) Equivalent dose is an intermediate step in the calculation of effective dose. Dose constraints, reference levels, and limits 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 tissue reactions but, as discussed in Section 2.2, these will be more appropriately set in terms of absorbed dose (Gy). Communication difficulties have arisen in situations where equivalent dose and effective dose expressed in the same units (Sv) have not been distinguished adequately; for example, in explaining doses for intakes of $^{131}$I for which the equivalent dose to the thyroid is more than 20 times the effective dose (Gonzalez et al., 2013). Such difficulties will be avoided if organ and tissue doses are referred to in terms of absorbed dose. For example, an intake of $^{131}$I might result in an effective dose of 10 mSv with a thyroid dose of 240 mGy. The use of equivalent dose as a distinct protection quantity is not required. While the Commission intends to discontinue the use of equivalent dose to set limits on organ/tissue doses to prevent tissue reactions, the quantity will remain as a step in the calculation of effective dose.

## 3.4. Effective dose

(43) Effective dose ($E$), as introduced in *Publication 60* (ICRP, 1991a) and applied in *Publication 103* (ICRP, 2007a), is defined as:

$$\begin{aligned} E &= \sum_T w_T \sum_R w_R D_{T,R} \\ &= \sum_T w_T H_T \end{aligned} \tag{3.2}$$

where $w_T$ is the tissue weighting factor for tissue $T$ and $\Sigma w_T = 1$, $D$ is absorbed dose, and $H$ is equivalent dose. The averaging is performed over all organs and tissues of the human body for which specific radiation detriment values have been calculated (Table 2.1) and tissue weighting factors have been specified (Table 2.3). Mathematically, effective dose is a weighted average of equivalent doses to organs/tissues. As outlined in Section 2.5, the $w_T$ values are chosen to represent the contributions of individual organs and tissues to the 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 2.3), despite the greater differentiation possible on the basis of relative detriment (Table 2.1), to avoid the impression of unwarranted accuracy in relation to effects of low-dose radiation.

(44) The SI unit of effective dose is the sievert (Sv), where $1\,\mathrm{Sv} = 1\,\mathrm{J\,kg^{-1}}$ in SI base units. Strictly, effective dose applies to the induction of stochastic effects at low doses or low dose rates. Consequently, 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 and management in the range of 20–100 mSv effective dose. There is no reason why effective doses should not be used as a quantity at doses >100 mSv; for example, as might be required as a short-term relaxation of worker doses in order to regain control in an accident. In principle, it could be used at doses up to approximately 1 Sv, but two factors need to be taken into consideration at higher doses:

- The potential for the occurrence of tissue reactions should be considered. For effective doses up to a few hundred mSv and for which irradiation is reasonably uniform throughout the body, severe tissue reactions would not be expected to occur. However, if there was a significant contribution to the effective dose from radionuclides concentrated in particular organs/tissues or localised external exposure, tissue damage could occur.
- A secondary consideration is that for doses >100 mSv (or more precisely, absorbed doses to organs and tissues >100 mGy of low-LET radiation) delivered at high dose rates ($>5\,\mathrm{mGy\,h^{-1}}$), the DDREF of 2 applied in determining solid cancer risk at low doses or low dose rates will not apply, so risks may be up to two times greater than implied by the nominal risk coefficients in *Publication 103* (ICRP, 2007a).

## 3.5. Committed dose

(45) Radionuclides incorporated into the human body irradiate organs and tissues over time periods determined by their physical half-life and their biological retention within the body. Radionuclides with long physical half-lives and long biological half-times may continue to deliver doses to body tissues over many years after intake. The need to control such exposures led to the definition of committed dose quantities (ICRP, 1991a, 2007a). 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:

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_T(t)\,\mathrm{d}t \tag{3.3}$$

where $\tau$ is the integration time following the intake at time $t_0$. Committed effective dose, $E(\tau)$, is then given by:

$$E(\tau) = \sum_T w_T H_T(\tau) \tag{3.4}$$

(46) The committed dose is assigned to the year in which the intake occurred. For workers and adult members of the public, the committed dose is integrated over the 50-year period following the intake. For infants and children, the dose is evaluated to 70 years of age.

(47) 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 $^{239}$Pu, for example, effective dose in the first year after intake will be generally <10% of the total committed effective dose. For most radionuclides, however, this effect will be much less significant, and for many, including $^{131}$I and $^{137}$Cs, 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.

## 3.6. Dose coefficients

(48) Revisions of ICRP recommendations invariably require recalculation of the dose coefficients (effective dose per unit exposure/intake) provided by the Commission because changes are made to the radiation and tissue weighting factors used in the calculation of equivalent and effective doses. 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 (ICRP, 2007a), incorporating a number of methodological improvements including revised and updated biokinetic and dosimetric models.

(49) *Publication 119* (ICRP, 2012b) provided a compilation of dose coefficients calculated according to *Publication 60* methodology (ICRP, 1991a). It referred back to previous publications that provided committed effective dose coefficients and committed equivalent dose coefficients for 3-month-old infants; 1-, 5-, 10-, and 15-year-old children; and adult members of the public and workers (ICRP, 1979, 1980, 1981, 1989, 1993, 1994a,b, 1995a,b, 1996a). It also included conversion coefficients for occupational exposures to external radiation, taken 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, 2015a) provided a compilation of dose coefficients for radiopharmaceuticals calculated using *Publication 60* (ICRP, 1991a) methodology,

referring back to previous publications (ICRP, 1987, 1998, 2008). The Commission has also provided dose coefficients for calculating doses to the fetus following maternal intakes, and for infants ingesting radionuclides transferred to breast milk (ICRP, 2001, 2004) based on *Publication 60* methodology.

(50) 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 Oak Ridge National Laboratory (Fisher and Snyder, 1967; 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.

(51) 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 adult Reference Male and Female (ICRP, 2002a), and the models were subsequently adjusted for consistency with these data. The use of male and female phantoms rather than the hermaphrodite MIRD phantoms requires explicit sex-averaging in the calculation of effective dose. Thus, in calculations relating to the 2007 Recommendations (ICRP, 2007a), equivalent dose is calculated separately for males and females, and averaged in the calculation of effective dose to the sex-averaged Reference Person (Fig. 3.2). The Commission has also developed a set of reference phantoms for children of different ages (ICRP, 2020a), and will provide reference phantoms for the pregnant woman and fetus.

(52) *Publication 116* (ICRP, 2010a) provided the first set of dose coefficients calculated using *Publication 103* (ICRP, 2007a) methodology and *Publication 110* (ICRP, 2009a) anatomical models, considering occupational exposures to external radiation. The radiations considered were mono-energetic photons, electrons and positrons, neutrons, protons, pions (negative/positive), muons (negative/positive), and He ions. The organ/tissue dose conversion coefficients tabulated in *Publication 116* represent ICRP/ICRU reference values. Comparisons of equivalent dose and effective dose with corresponding operational quantities (see Section 3.8) showed the latter to provide conservative estimates of dose in the majority of cases.

(53) *Publications 130*, *134*, *137*, and *141* (ICRP, 2015b, 2016, 2017, 2019a) provided methodology and updated dose coefficients and bioassay data for internal exposures of workers. The final report in this series is in preparation. Work is in progress on replacement dose coefficients for radionuclide intakes by members of the public and for radiopharmaceutical administrations to patients. For the first time,

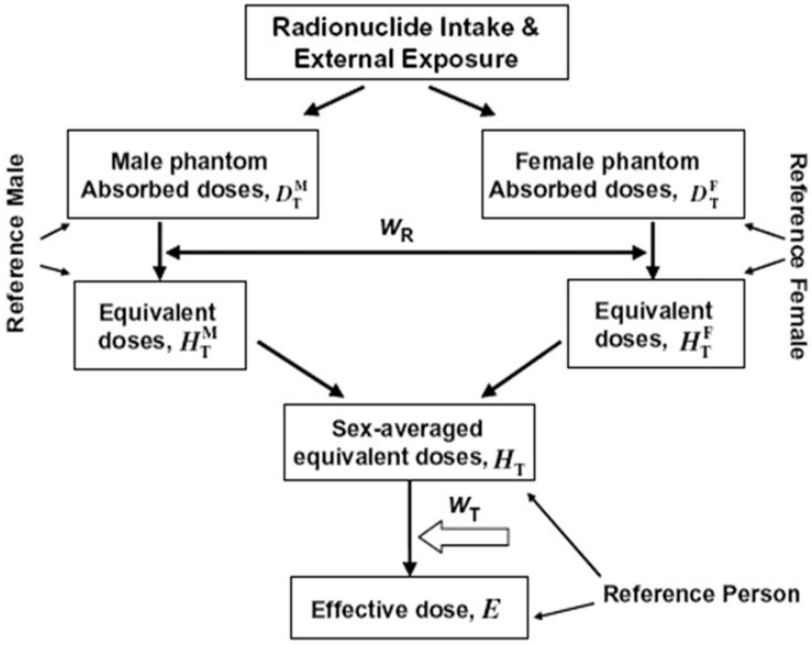


Fig. 3.2. Sex-averaging in the calculation of effective dose using *Publication 110* (ICRP, 2009a) reference phantoms.

dose coefficients have also been provided for exposures of members of the public, including children, to external sources (ICRP, 2020b).

## 3.7. Collective dose

(54) For the purposes of optimisation of radiological protection, the Commission has introduced the collective dose quantities (ICRP, 1977, 1991a, 2007a). These quantities take account of the group of persons exposed to radiation and the period of exposure. They represent the sum of all individual doses from a source over a specified time period. The quantities have been defined as the collective equivalent dose, $S_T$, which relates to tissue or organ $T$ and the collective effective dose, $S$ (ICRP, 1991a, 2007a). The special name used for the collective dose quantity is the 'man sievert'.

(55) To avoid aggregation of, for example, very low individual doses over extended time periods and wide geographical regions, ideally, limiting conditions need to be set. Whenever possible, the dose range and the time period should be

stated. The collective effective dose, $E$, due to individual effective dose values between $E_1$ and $E_2$ is defined as:

$$S(E_1, E_2, \Delta T) = \int_{E_1}^{E_2} E \frac{\mathrm{d}N}{\mathrm{d}E}\, \mathrm{d}E \tag{3.5}$$

where $\mathrm{d}N/\mathrm{d}E$ denotes the number of individuals who are exposed to an effective dose between $E$ and $E + \mathrm{d}E$, and $\Delta T$ specifies the time period within which the effective doses are summed. The Commission has given advice on the use of collective dose as a tool for optimisation of protection in *Publication 101* (ICRP, 2006), taking account of the need to disaggregate doses when necessary to allow separate consideration of homogenous parts of the dose distribution in time and space.

(56) The use of collective effective dose relies on the validity of application of the LNT dose–response model, and the additivity of doses from different types of radiation exposure. It is used, for example, by UNSCEAR (2008, 2012a) to compare doses from different sources of radiation. Collective effective dose is not intended as a tool for epidemiological risk assessment, and it is also inappropriate to use it in formal risk projections. In particular, the computation of numbers of cases of cancer based on collective effective doses involving extremely low exposures to very large populations should be avoided. Owing to the large uncertainties associated with such estimates, the results will be more misleading than informative (ICRP, 2007a).

(57) There can be situations where the estimation of health effects from collective effective doses can be useful for planning of radiation protection actions if treated with appropriate caution. For example, following a severe nuclear accident or in advance planning for such events, an assessment of collective effective dose could be used to give an indication of possible health impact to help with planning and selecting from various protection options. In retrospective assessments of planned or existing exposure situations, assessments of collective effective dose can provide initial screening evaluations of possible health impact to inform medical and epidemiological evaluation. It is essential that such analyses using collective effective dose include consideration of background rates of health effects in the population, including morbidity and mortality, and consider uncertainties. Comparisons with appropriate baseline disease incidences will determine whether epidemiological analyses may provide statistically meaningful results for exposed populations.

## 3.8. Operational quantities

(58) 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 (ICRP, 2015b). For the monitoring of external exposures, operational dose equivalent quantities for area and individual monitoring have been defined by ICRU (1985, 1988, 1993, 2020). 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 reasonable estimates of effective dose, and doses to the lens of the eye and skin.

(59) For individual monitoring, 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, depth $d = 10$ mm and $H_p(10)$ have 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 the value of $H_p(10)$ provides a reasonable estimate of effective dose. For assessment of the dose to the skin and to the extremities, the personal dose equivalent, $H_p(0.07)$, with depth $d = 0.07$ mm, is recommended for use as an operational quantity. For the case of monitoring the dose to the lens of the eye, depth $d = 3$ mm has been proposed. Although *Publication 103* (ICRP, 2007a) considered that measurement of $H_p(3)$ may be unnecessary, the increased importance of eye protection with the reduction in the dose limit for the lens of the eye (ICRP, 2012a) has led to a re-evaluation of its application (ICRP, 2010a; Bolch et al., 2015). In some situations in which individual monitoring is not carried out, an assessment of effective dose may be performed by area monitoring applying ambient dose equivalent, $H^*(10)$.

(60) The set of ICRU operational dose quantities in current use was defined more than 30 years ago. Following from *Publication 116* (ICRP, 2010a) which provided updated dose coefficients for occupational exposures to external sources using the reference adult phantoms (see Section 3.6), ICRU (2020) has reviewed the definition of the operational quantities. Shortcomings were identified in their definition, including that the published conversion coefficients were calculated using the kerma approximation (i.e. without consideration of energy transport by secondary charged particles), and that the operational quantities are not good approximations for effective dose at low energies and high energies. The review resulted in suggestions for new definitions of operational quantities for individual and area monitoring. The proposal for personal dose equivalent, $H_p(10)$, and ambient dose equivalent, $H^*(10)$, is to redefine them as the product of fluence or air kerma and conversion coefficients derived from the maximum of the conversion coefficient curves for effective dose as a function of particle energy for all particles considered in *Publication 116*. As a consequence, these operational quantities, renamed personal dose, $H_p$, and ambient dose, $H^*$, will be defined implicitly in the reference anthropomorphic phantoms, resulting in improved coherence and simplification of the system (ICRU, 2020). Furthermore, the operational quantities for measurement of eye and skin doses will become absorbed dose quantities, consistent with the change proposed in this publication to use absorbed dose instead of equivalent dose to set limits to prevent

tissue reactions. As personal dose, $H_p$, and ambient dose, $H^*$, are related directly to effective dose, and because absorbed dose will be used in the measurement of eye and skin doses, the use of $Q(L)$ to define radiation quality in the calculation of dose equivalent will be discontinued.

# 4. OCCUPATIONAL AND PUBLIC EXPOSURES

(61) The use of effective dose is well established for controlling and monitoring occupational and public exposures. It provides a robust approach to enable absorbed doses from external and internal exposures to different organs and tissues from a variety of different sources and types of radiation to be summed and compared with appropriate dose constraints, reference levels, and limits. These dose criteria 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 the whole period of employment or whole 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.

## 4.1. Occupational exposures

(62) Effective dose is an important tool for the management of all types of occupational exposure situations. In planned exposures, it is used in prospective assessments for optimisation of radiological protection, and to ensure that operations will be carried out within the relevant dose limits and dose 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 choosing between protection options when planning complex work involving multiple workers, where it is important to consider collective exposures as well as exposures of 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. Individual and collective 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, taking account of the economic and societal impacts of each option (ICRP, 2007a).

(63) Retrospective assessments of effective dose for occupational exposures in planned exposure situations 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 implemented adequately. Effective dose is calculated for both external and internal irradiation, and will often be based on specific measurements (e.g. from a personal dosimeter or radionuclides in urine). However, although effective dose is estimated for a specific individual, 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 the use of individual-specific parameter values (e.g. taking into account body size or sex) and, as noted earlier, dose constraints, reference levels, and limits are set to apply to all workers; this pragmatic approach to

protection is equitable and workable (see Para. 80). The pregnant worker is treated as a special case once pregnancy is declared, limiting effective dose to the fetus to provide a level of protection that is broadly similar to that provided for members of the public.

(64) For external irradiation, while effective dose is the primary quantity that should be evaluated, it may also be necessary to explicitly evaluate doses to the lens of the eye, the skin, and the hands and feet. The specific occupational dose limits for these organs and tissues (Section 2.2) 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 3.8, 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 reasonable estimate of effective dose for most exposure situations. Similarly, $H_P(0.07)$ can be used as a reasonable estimate of equivalent dose to the skin in most circumstances, and while $H_P(0.07)$ also provides an adequate measure of equivalent dose to the lens of the eye for photons, $H_P(3)$ provides a better measure for electrons of lower energies (ICRP, 2010a; Bolch et al., 2015).

(65) 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 lens of the eye. Where appropriate, adjustment factors may be used to provide approximate evaluations indicative of likely levels of effective dose. 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 (Martin and Magee, 2013). Clinicians performing interventional procedures may wear two dosimeters – one beneath the apron and the other on the apron – and various formulae are applied to estimate effective dose (ICRP, 2018). More specific information may be required on dose to the lens of the eye or dose to the protected tissues to enable a more realistic value to be determined for effective dose. In the rare case of a significant contribution of weakly-penetrating radiation to external exposure, the contribution of the skin dose to effective dose also needs to be considered.

(66) For internal exposures, committed effective doses are determined retrospectively based on the results of individual monitoring or, in particular 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 (e.g. thyroid counter), 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 coefficients then give values of effective dose for the estimated intakes. Calculations are done using reference biokinetic models and reference dose coefficients as published by the Commission (see Section 3.6). 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. As 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 on solubility in the calculation of doses from inhaled radionuclides have been given by the Commission (ICRP, 2002b, 2016, 2017).

(67) The Commission 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, for example, be based on a series of measurements of radionuclides in urine for a particular individual. The standard models used to estimate effective dose 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. Such changes may be considered reasonable, but the resulting estimates of doses should be clearly distinguished from the standard calculation of effective dose; if it is agreed that such dose information should be added in the individual's dose record, this difference should be noted.

(68) 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 (see below).

(69) Existing exposure situations are those in which the source is 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 $^{222}$Rn and progeny, is addressed in *Publication 126* (ICRP, 2014). The use of naturally occurring radioactive materials in various industries is the subject of Publication 142 (ICRP, 2019b). For existing exposure situations, the use of effective dose is an appropriate basis for decisions on whether control measures are required. Similar considerations apply to those addressed above for planned exposures.

(70) Emergency exposure situations may arise in the workplace during the operation of a planned exposure situation and any other unexpected situation that 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 can provide an initial indication of whether exposures are such that tissue reactions could be observed, and individual organ doses need to be considered in the control of any further exposures. At a later stage, a full retrospective risk assessment may be required following overexposures in which effective dose will have only an initial role. Risk to individuals should be evaluated in such circumstances using best estimates of organ/tissue doses; appropriate RBE data; and age-, sex-, and population-specific risk factors (see Section 2.6).

(71) The second situation is in the immediate aftermath of an accidental release or in an ongoing emergency in which intervention by 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, or of other organs if there are significant intakes by inhalation (the use of personal protective equipment should control internal exposures in such circumstances). As discussed in Section 3.4, there is no reason, in principle, why effective dose should not be used as a protection quantity at doses $>100$ mSv in accident situations. However, caution would be required in such circumstances to avoid tissue reactions, particularly when considering doses from external exposures of the skin and lens of the eye, and internal exposures from radionuclides that concentrate in particular organs.

(72) 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 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 will need to be assessed by occupational health physicists and medical staff. The Commission 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, NCRP, in collaboration with the Commission, has developed a biokinetic and dosimetric model for such exposures (NCRP, 2007). The dose coefficients and data given by the Commission could therefore be used in conjunction with the NCRP wound model parameter values to obtain estimates of organ/tissue doses and effective dose for radionuclides that have entered the blood from the wound site.

## 4.2. Public exposures

(73) Planned exposure situations in which members of the public may be exposed to external and internal sources include the following:

- visits to controlled or supervised areas;
- access to areas accessible to members of the public adjacent to controlled areas;
- controlled discharges of radioactive material to the environment;
- environmental releases following disposal of solid radioactive waste; and
- use of consumer products containing radioactive material.

(74) 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 (see Para. 79) are below the relevant dose constraint for the public; such assessments are carried out using modelling. Retrospective assessments may be carried out to demonstrate compliance with dose limits and for comparison with dose constraints. Ideally, such assessments would be based on monitoring of the environment. 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.

(75) Existing exposure situations arise from:

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

(76) For existing exposure situations, prospective assessments are carried out to determine the annual effective dose to the Representative Person (see para. 79) as an input to optimisation studies using 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 the use of past monitoring data to estimate future effective doses. Measurements of environmental concentrations of radionuclides and estimates of dose to members of the public can be used, if available, for retrospective assessments of annual effective dose for comparison with the relevant reference level of effective dose.

(77) Emergency exposure situations may occur during the operation of a planned exposure situation, from a malicious act, or from any other unexpected situation, and may require precautionary and/or urgent protective actions in order to avoid or reduce radiation exposures. 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 accident scenarios 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; for example, for accidents involving releases of $^{131}$I, 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, as well as young children, may also be important, particularly in relation to triage and communication.

(78) Retrospective assessments of effective dose due to emergency exposures may be required to assess the need for medical follow-up. In such cases, individual monitoring data (external and internal exposures) and/or biological dosimetric measurements would be required, as well as measurements of radionuclide concentrations 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 modelling results. In such situations, 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, highlighting the importance of interpreting estimates of effective dose with care. Retrospective assessments can also be used to refine the prospective dose assessments to reduce uncertainties and to improve the optimisation process.

(79) Effective dose is usually assessed for a person or group of people who are identified to be representative of the more highly exposed individuals in the population and termed the 'Representative Person'. This concept was introduced in *Publication 101* (ICRP, 2006) to replace the less quantitatively defined concept of the 'Critical Group'. A number of possible groups of people of different ages with different occupations, habits, and food consumption rates would generally be considered in order to define the Representative Person.

(80) In the dose assessment process, a number of Reference Persons of different ages can be considered: the Commission provides dose coefficients for 3-month-old infants; 1-, 5-, 10-, and 15-year-old children; and adults (see Section 3.6). In addition, the Commission considers doses to the embryo/fetus and 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 with doses received by the adult. However, this is not always the case, and for four radionuclides – $^{32}$P, $^{33}$P, $^{45}$Ca, and $^{89}$Sr – 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 1 year are required for comparison with dose criteria, it may be adequate to carry out a simplified dose assessment using the annual intake of radionuclides by

the mother, and applying dose coefficients for chronic exposure of the embryo/fetus throughout pregnancy (HPA, 2008). If a more detailed assessment is required, the annual intake by the mother may be assumed to occur over the 9 months of pregnancy and 3 months of breast feeding. External doses to the embryo/fetus are taken to be the same as to the maternal uterus. Dose coefficients for external exposures of children are also now available (Section 3.6; ICRP, 2020b). *Publication 101* (ICRP, 2006) concluded that consideration of three age groups – 1- and 10-year-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. In general, uncertainties in estimating exposures are large in comparison with differences in dose coefficients for different age groups. It is recognised that stakeholders may make requests for dose estimates for additional age groups, and such calculations are appropriate to facilitate dialogue.

(81) 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 (Streffer, 2004). The weighting factors are used to allow for the contribution of individual organs and tissues to total stochastic detriment 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 (ICRP, 2003a). Dose control criteria (dose constraints and reference levels) can be set in the knowledge of potential differences between age groups in detriment per Sv. The use of dose constraints and reference levels that apply to all members of the public (or all workers), together with optimisation, provides a pragmatic, equitable, and workable system of protection that does not distinguish on an individual basis. The corollary is that, for practical radiation protection purposes, the use of a single set of tissue weighting factors has been considered to be appropriate.

(82) In modelling of radionuclide transfer in the environment and internal doses received by members of the public, an important issue is the selection of the most appropriate physical and chemical characteristics of radionuclides. This consideration is of particular importance for prospective assessment of facilities at a pre-operational stage and for emergencies. Previous experience of similar situations is likely to be instructive when monitoring data and information on radionuclide characteristics are available. The Commission advises 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).

(83) In most situations, direct measurements of external and internal exposures of the public are not available, and assessments of effective doses are 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 and for comparison with dose constraints and reference levels. 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, 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 adverse consequences for the affected population.

## 4.3. Potential exposures

(84) Planned exposure situations involve the acceptance and control of certain levels of exposure of workers and members of the public. In addition, higher levels of exposure may arise following unanticipated deviations from planned operating procedures, accidents including loss of control of the radiation source, and malevolent events. Such occurrences are referred to as 'potential exposures' (ICRP, 2007a). Deviations from planned operating procedures and accidents, although rare, may be foreseen and the probability of occurrence estimated. Loss of control of radiation sources and malevolent events are less predictable and call for case-by-case approaches.

(85) The evaluation of potential exposures usually involves: (1) construction of scenarios which represent the events leading to exposures; (2) assessment of the probabilities of these events; (3) assessment of the resulting dose and associated detriment; and (4) comparison with some criteria of acceptability. Decisions on acceptability will depend on both the probability of occurrence and the magnitude of the resulting dose and risk. These factors may be considered separately, but they can also be combined to consider the probability of health effects attributable to the radiation exposure occurring as a result of the unlikely event. In this context, the Commission (ICRP, 2007a) has considered the risk of fatal cancer using a value of $5 \times 10^{-2}$ per Sv. The probability of death is taken as the product of the probability of occurrence of the event and the fatal cancer risk associated with the effective dose that would be received if the event occurs. The resulting probability is compared with a risk constraint to judge acceptability.

(86) Risk constraints, like dose constraints, are source-related and in principle should equate to a health risk similar to that implied by the corresponding dose constraint for the same source. However, as discussed in *Publication 103* (ICRP, 2007a), the uncertainties associated with estimation of the probability of occurrence of such events are large, so the use of a generic risk constraint is likely to be

appropriate. For potential exposures of workers, the Commission recommends the use of a generic risk constraint of $2 \times 10^{-4}$ year$^{-1}$ on the basis that this corresponds to the fatal cancer risk associated with an average annual occupational exposure of 5 mSv (i.e. assuming a fatal cancer risk of $5 \times 10^{-2}$ per Sv effective dose) (ICRP, 2007a). An effective dose of 5 mSv is referred to as a typical high value received in certain types of operation after optimisation of protection. For potential exposures of the public, the Commission (ICRP, 2007a) recommends a risk constraint of $1 \times 10^{-5}$ year$^{-1}$.

(87) In addition to the basic approach of setting generic risk constraints based on fatal cancer risks, it is recognised that lower-probability, higher-dose events might also result in the exceedance of threshold doses for tissue reactions, and this factor also needs to be taken into account.

# 5. MEDICAL EXPOSURES

(88) Radiation is used in a wide range of applications in medical diagnosis and therapy. The radiation doses received by patients in diagnostic and interventional procedures are recorded in terms of quantities that can be measured for each technique. These measured quantities can be applied through straightforward methods for assessment of dose levels, and are used for comparisons of doses for particular types of examination among different healthcare facilities and around the world. Surveys are made to establish diagnostic reference levels in terms of these measurable quantities (Martin, 2008, 2011; ICRP, 2017a).

(89) As stochastic risks vary according to the organs and tissues irradiated in different medical procedures, measurable dose quantities do not convey a meaningful indication of the associated relative health detriments from alternative techniques that result in different distributions of absorbed dose within the body. Effective dose can be used to make comparisons between doses from medical procedures that expose different regions of the body. It has been instrumental in raising awareness of dose levels from diagnostic procedures and providing a broad understanding of possible risks associated with these radiation exposures. Effective dose is used commonly in training medical professionals in radiological protection. It is employed in making informed judgements to aid in justification of medical procedures and in establishing dose constraints for patient carers and for volunteers in medical research. Effective dose has provided a useful reference for the improvement of radiological protection in medical practice, and gives a means of conveying an indication of radiation dose relating to possible risks to health that can be understood by clinicians and non-specialists in radiological protection.

(90) This chapter sets out applications for which effective dose can be used, where there is a need to provide an indication of health risk, and those for which it is not recommended, where other measurable dose quantities are sufficient to provide the information required. Evidence is presented in support of the use of effective dose as an approximate indicator of possible risk, illustrating the relationship between effective dose and risk for a range of diagnostic x-ray procedures and changes in risk for males and females with age at examination.

## 5.1. Effective doses from medical procedures

(91) Effective doses from medical procedures are calculated using dose coefficients that relate measurable quantities to the protection quantities. The Commission has published dose coefficients for diagnostic procedures in nuclear medicine (see Section 3.6), but has not, at this time, provided such coefficients linked to diagnostic x-ray imaging procedures. However, a number of organisations have published coefficients that can be used in the calculation of values for organ/tissue doses and effective doses for radiology procedures. These can be applied to the entrance surface air kerma or kerma area product for radiography and fluoroscopy (Jones and Wall, 1985;

Table 5.1. Examples of typical effective doses (mSv) for adults in three countries from some common examinations.

| Procedure | UK* | USA† | Russian Federation‡ |
|---|---|---|---|
| *Radiography* | | | |
| Chest PA | 0.01 | 0.03 | 0.1 |
| Chest Lat | 0.04 | 0.07 | 0.18 |
| Lumbar spine AP | 0.39 | 2.0 | 0.6 |
| Lumbar spine Lat | 0.21 | – | 0.6 |
| Abdomen AP | 0.43 | 0.6 | 1.0 |
| Pelvis AP | 0.28 | 0.4 | 0.7 |
| *Interventional* | | | |
| Coronary angiography | 3.9 | 15 | 15 |
| Femoral angiography | 2.3 | 7 | 5–10 |
| *Computed tomography* | | | |
| CT head | 1.8 | 1.6 | 1.8 |
| CT chest | 14 | 6.1 | 6.3 |
| CT abdomen | 16 | – | 9 |
| CT abdomen + pelvis | 13 | 7.7 | – |
| CT chest + abdomen + pelvis | 19 | 12 | 25 |
| *Nuclear medicine* | | | |
| Bone scan: $^{99m}$Tc | 3 | 4 | 3 |
| PET whole-body tumour imaging ($^{18}$F FDG)§ | 7.6 | 13 | 5 |

PA, postero-anterior; AP, anteroposterior; Lat, lateral; CT, computed tomography; PET, positron emission tomography; FDG, fluorodeoxyglucose.
*Wall et al. (2011), Shrimpton et al. (2016), and ARSAC (2020).
†Mettler et al. (2008).
Alessio et al. (2015), Smith-Bindman et al. (2015), Becker et al. (2016), Kanal et al. (2017), and NCRP (2019).
Zvonova et al. (2015), Chipiga and Bernhardsson (2016), Vodovatov et al. (2016), and Balanov et al. (2018).
§Doses are for PET tumour imaging from $^{18}$F only and do not include CT which is frequently performed with PET.

Hart et al., 1994; Rannikko et al., 1997; Kramer et al., 2004), or the dose–length product for CT (ImPACT, 2011; Wall et al., 2011; Lee et al., 2011, 2012; Ding et al., 2015; Shrimpton et al., 2016). Daily decisions for justifying individual patient imaging exposures, or for optimising protection through selecting the most appropriate technique, require approximate estimates of dose relating to inferred risks to health. Generic values of effective dose provide a straightforward tool with enough information about general radiation exposure levels linked to detriment for the purpose of

making these everyday decisions. Ideally, these generic values should be based on data that apply to the country and facility under consideration. Variations result from differences in equipment, techniques, and patient selection (weight range), as exemplified by the range of values for a selection of examinations derived from surveys in different countries given in Table 5.1. Some of the differences apparent in this table are due to varying definitions of examinations, and reflect doses from techniques and equipment in use at the time the surveys were performed, which will change with time. However, there are differences of up to 25% in some data caused by the use of different phantoms and dose conversion coefficients. Recognising the need to help standardise such dose calculations, the Commission will, in future, provide reference dose coefficients for specified radiographic and CT procedures. It should be noted that the values in Table 5.1 and those used in the applications in the next section relate to a Reference Person and not to any specific individual, although the dose might be calculated in relation to an individual patient's exposure.

## 5.2. Applications using effective dose

### 5.2.1. Referral guidelines and justification of procedures

(92) The Commission (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 procedure 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 medical condition.

(93) The first level of justification occurs at the national level when radiation equipment and techniques are approved for purchase and use in hospitals and other medical installations. The second level is reflected in referral guidelines for diagnostic procedures produced by professional societies and health authorities, and here effective dose is used to provide information on the relative magnitudes of doses from different types of examinations (EU, 2000; ACR, 2020; EANM, 2020).

(94) Clinicians (e.g. referring clinicians and radiologists) are responsible for carrying out the third level of justification for each patient. This process will be determined by the need for diagnostic information but, in addition to the benefit for the patient, the potential risk from the radiation exposure should be considered. Effective dose can provide sufficient information for this assessment, also taking account of the sex and age of the patient (see Section 5.4), the medical risk of a proven or suspected disease, and the life expectancy of the patient (Loose et al., 2010).

### 5.2.2. Choice of imaging technique

(95) Patient imaging procedures typically involve partial-body radiation exposures and exposure of tissues with differing sensitivities in terms of radiation-related cancer

risk (see Sections 2.6 and 5.4). Effective dose enables the straightforward comparison of doses from different procedures in which the dose distribution can be very different for both machine-produced x-ray and nuclear medicine procedures.

(96) When two different x-ray imaging modalities are considered, the primary factor determining the choice will be the potential benefit to the patient, but comparison of effective dose can be a secondary factor in guiding a referral test selection. For example, a chest CT examination and a conventional chest x ray both irradiate the lungs, but the spatial distribution of radiation dose within the body is different and the effective dose from CT can be a few hundred times that of chest radiography. If the necessary information can be provided by both chest CT and chest radiography for a particular clinical question, the difference in effective dose (even if crudely estimated) supports the choice of chest radiography, but the prime consideration must be which modality will provide more benefit for the patient.

### 5.2.3. Optimisation of technique

(97) Once a decision is made regarding an imaging procedure, the next step is to ensure its optimisation. Effective dose is not the best quantity for making comparisons between doses for the same or similar techniques applied in different departments or institutions; modality-specific dose quantities (e.g. kerma area product, volume-averaged CT dose index) should be used for this purpose (see Section 5.3). However, in circumstances in which the dose distributions within the body are substantially different, and doses to a number of organs and tissues within the trunk need to be considered, the use of effective dose is appropriate. One example is when using different radiographic projections [e.g. postero-anterior (PA) as opposed to anteroposterior (AP)] for chest radiography, as the breasts, lungs, and oesophagus receive a higher dose in AP than PA and make a greater contribution to effective dose (Martin et al., 1999; Martin and Sutton, 2014). Another example is the use of different tube potentials (kV) (Martin et al., 1993) or very different x-ray tube filtration (e.g. in paediatric radiology or interventional procedures). Here, increasing the kV will give more penetrating radiation, so the exposure level can be reduced, lowering the dose to more superficial tissues (Martin et al., 1993; Martin, 2007b, 2008; Martin and Sutton, 2014).

### 5.2.4. Doses to research volunteers

(98) Exposures incurred by volunteers as part of a programme of biomedical research are considered as medical exposures (ICRP, 1991b, 2007b; IAEA, 1995, 2011). Before a research proposal is approved, an evaluation of possible detriment for the individuals involved must be made and recorded. Effective dose is the appropriate quantity to use for summing the possible radiation-related health detriments that may accrue from the various procedures that are to be performed to support the research objectives, each of which may have a different dose distribution within the body (IAEA, 2011). However, it should be recognised that effective dose is estimated

for a Reference Person. When considering potential radiation-related risks in research subjects, cognisance should be taken of age, sex, and health status (see Section 5.4).

### 5.2.5. Reporting of unintended exposures

(99) Unintended exposures and overexposures of patients in diagnostic procedures can be assessed initially using effective dose, which can provide sufficient information for the incident investigation and report, and inform decisions on requirements for more detailed assessments. An unintended exposure could occur in various situations, such as when there has been an error in the referral process, or the wrong patient or body part was examined. An overexposure might occur when there has been a mistake in the procedure, or where an equipment fault has occurred (Martin, 2005; Martin et al., 2017). In situations of unintended exposure in which the level of dose is low, a broad assessment in terms of effective dose will usually be sufficient. If the unintended exposure is known to be similar to the dose for the standard examination of that type, generic values of effective dose for that procedure can be used if the generic value is a few mSv or less. 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 the effective dose is greater than a few tens of mSv, there is likely to be a perceived need for a more in-depth evaluation involving an assessment of risk for the individual. In these circumstances, it may be appropriate to estimate doses for all radiosensitive organs and tissues, and apply age-, sex-, and organ-specific risk coefficients to derive a best estimate of risk (see Sections 2.6 and 5.4).

### 5.2.6. Evaluating the efficacy of imaging for health screening or non-medical applications

(100) Effective dose can be used in evaluation of health screening procedures that involve exposure of many organs/tissues within the trunk (with the exception of mammography, in which the breast receives the majority of the dose). Effective dose to a Reference Person is useful for evaluating doses from techniques such as dual x-ray absorption that irradiate either the whole or part of the body for which a quantity linked to health detriment may be required, even though the dose is extremely low, simply to put the doses received into context. This is considered appropriate, despite the dose level being far below that where any stochastic effects can be demonstrated, because effective dose is a quantifiable measure of doses to organs/tissues known to be sensitive to radiation (see Section 5.4).

### 5.2.7. Doses to carers

(101) 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 exposures. A typical example is the exposure of family members of a patient discharged after thyroid treatment with unsealed $^{131}I$, or patients who have implanted sealed sources. Assessments of potential exposures and doses received will need to be made from time to time, and the appropriate quantity is effective dose, as for occupational and public exposures. The acceptability of doses will depend on the individual circumstances (ICRP, 2007a).

### 5.2.8. Education and training of clinicians and other healthcare professionals

(102) Referring clinicians and other medical professionals who perform medical procedures involving radiation may have little understanding of the potential health detriment from radiation exposure because it is perceived to be so small compared with the benefits of medical exposures (ICRP, 2009b; Loose et al., 2010; Zanzonica and Stabin, 2014). Consequently, it is difficult for them to take these potential risks into account when requesting or justifying patient diagnostic or interventional exposures, or when explaining possible risks to their patients. Effective dose is a single value which can be used to compare various exposure scenarios, and a knowledge of typical effective doses from common procedures should therefore be included in the education and training of medical practitioners. Collective effective doses from medical procedures in different countries and average per caput doses derived from them have been used to raise awareness of exposures and changes over time (UNSCEAR, 2008; NCRP, 2009, 2019; Wall et al., 2011).

(103) Medical practitioners are also one of the first groups approached by members of the public for advice and reassurance in the event of a radiation exposure or an accident involving potential radiation exposure of the public. When only the possibility of stochastic effects is involved (as in the majority of cases), effective dose is an appropriate quantity for straightforward communication and to facilitate comparisons of the possible health risks of an exposure with risks from other exposure scenarios.

## 5.3. Applications for which effective dose is not recommended

(104) Effective dose is a useful tool when comparisons are needed relating to health detriment. However, there are many situations where the dose quantities that are used for practical measurements will provide sufficient information. Here, measurable dose quantities that are recorded or displayed on equipment should be used in order to simplify the recording process and avoid use of unnecessary approximations and adjustment factors. As tissue weighting factors may evolve further with time and organ/tissue dose calculation methods may improve, the availability of raw data will allow more accurate calculations to be performed in the future, where they are needed. Applications for which these and other dose quantities provide a better option, and for which effective dose is not recommended, are listed here.

### 5.3.1. Comparison of doses for similar techniques and setting diagnostic reference levels

(105) Measurable dose quantities such as entrance surface air kerma and kerma area product for radiography and fluoroscopy, and volume-averaged CT dose index and dose–length product for CT are suitable for making comparisons between facilities, machines, and techniques that deliver exposures with similar relative distributions of absorbed dose inside the body. They should be used for undertaking surveys of patient doses and to set diagnostic reference levels.

### 5.3.2. Recording patient dose information in reports for medical procedures

(106) Measurable dose quantities should be used where dose information relating to patient exposure forms part of reports for medical radiological procedures, as required by EURATOM 59/2013 for European Union member states and for accreditation by the Joint Commission on Accreditation for Healthcare Organizations in the USA.

### 5.3.3. Tracking of patient doses

(107) As the use of radiation for medical imaging has increased, the number of patients who receive repeated imaging procedures has also risen (Sodickson et al., 2009). Dose tracking methods are being developed for recording patients' accumulated radiation exposure from medical imaging procedures over time in order to provide more formal ways to quantify these doses (Rehani et al., 2014; Rehani, 2015). These data are best recorded using measured dose quantities (Rehani et al., 2014), but when there is a requirement for more information, calculations of organ/tissue and effective doses and their summation as cumulative doses will aid understanding of potential risks for individual patients (Brambilla et al., 2020; Rehani et al., 2020).

### 5.3.4. Assessment of doses where only one organ is exposed

(108) When radiological imaging is limited predominantly to one anatomical area, such as in mammography of the breast or the brain in head CT, estimates of organ or tissue dose should be used instead of effective dose, together with estimates of organ/tisue-specific risks. Similarly, assessments of doses from imaging procedures involving radioiodine uptake by the thyroid should primarily be quoted in terms of absorbed dose to the thyroid, which is the predominant organ/tissue irradiated. Gonad dose should be used for evaluation of examinations in which doses to the reproductive organs make up the majority of the dose, noting that the calculation of effective dose includes averaging of doses to males and females (see Sections 2.4 and 2.5).

## 5.4. Effective dose and risk communication

### 5.4.1. Communication of doses and associated health risks

(109) For discussions regarding justification and optimisation of examinations and for communication with patients, clinicians need special training and language to describe radiation dose that reflects a broad perspective of risk. The complexities of risk communication are beyond the scope of this publication, but Table 5.2 gives a scale linked to effective dose in the context of risks and benefits from medical imaging, with general terms to describe the dose linked to possible levels of cancer risk and examples of procedures within different dose ranges. The terms used for effective doses $\geq$1 mSv are the same as applied by UNSCEAR (2012a) to whole-body absorbed doses (mGy) in the same ranges. Thus, the inferred risk from an exposure giving an effective dose of 10–100 mSv can be considered to be low in this specific context, while that for effective doses in the range of 1–10 mSv can be considered to be very low, equating to the exposures that individuals get every year simply from living on Earth through exposure to natural background radiation. The excess risk from an effective dose <0.1 mSv, which includes examinations such as chest x rays, is categorised in this scheme as negligible; an alternative term might be extremely low. These terms are slightly different from those used in *Publication 62* (ICRP, 1991b) for medical research, but the population groups and purposes for the exposures are different.

(110) Clinicians and patients will sometimes need more information in order to put radiation exposures and possible risks into context. For this purpose, comparisons can be helpful with those radiation doses from situations with which the individuals are familiar, and for which they accept the risk. Examples of everyday exposures are those from natural background radiation and the dose that an individual might receive from cosmic rays during an aeroplane flight. These comparisons can be particularly useful for patients who have concerns about the procedures that they are undergoing, but who have little or no knowledge about radiation and may, as a result, have an unrealistic fear of the potential harm from radiation exposure. Comparisons using effective dose can be instrumental in educating medical practitioners, patients, and the public by helping to provide a broader perspective of possible risks from radiation exposure. The potential risk from medical exposures is generally lower than for a reference population due to the higher average age of patients and competing disease-related risks with reduced life expectancy, although paediatric populations serve as an exception. Further, the risk of radiation exposures in interventional radiology replaces the higher risks of alternative surgical therapies in many cases.

Table 5.2. Effective dose ranges and terminology for describing risks from different medical diagnostic procedures for adult patients of average age (30–39 years) based on UK data.*

| Effective dose (mSv) | Risk of cancer | Proposed term for dose level | Examples of medical radiation procedures within different dose categories‡ |
|---|---|---|---|
| <0.1 | Inferred $<10^{-5}$ on LNT model | 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 | Inferred $10^{-5}$–$10^{-4}$ on LNT model | 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 | Inferred $10^{-4}$–$10^{-3}$ on LNT model | 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; lung perfusion $^{99m}$Tc for imaging lung perfusion; $^{99m}$Tc imaging of bone lesions; cardiac stress tests; $^{99m}$Tc SPECT imaging; imaging with $^{18}$F, $^{123}$I, and $^{111}$In. |
| 10–100 | Risk $10^{-3}$–$10^{-2}$ based on LNT model and epidemiology† | 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; endovascular aneurysm repair (10–35 mSv).<br>Renal/visceral angioplasty; iliac angioplasty; follow-up of endovascular aneurysm repair (35–100 mSv). |
| 100s | $>10^{-2}$ based on epidemiology† | Moderate | Multiple procedures and follow-up studies. |

LNT, linear non-threshold; CT, computed tomography.
*Martin, C.J., 2007a. (2007a), Wall et al. (2011), and Martin and Sutton (2014).
†Risk bands are lifetime detriment-adjusted cancer incidence to nearest order of magnitude.
‡Effective doses based on UK data for diagnostic procedures and ICRP (2010b) for interventional radiology.

### 5.4.2. Age- and sex-specific cancer risks and effective dose

(111) As discussed in Section 2.6, 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 estimated risks of lifetime cancer incidence were shown 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 (see Section 2.6). Considering all cancer sites combined, lifetime risk of excess cancer incidence compared with those for the age 30–39 years at exposure group were estimated to be greater by a factor of approximately 2–3 for exposures of young children aged 0–9 years, and less by a similar factor for adults aged 60–69 years. Some cancer types showed greater dependence on age at exposure, notably thyroid cancer, while others showed little or no age dependence, including lung cancer [see also UNSCEAR (2013)].

(112) Based on the methodology described in Section 2.6 to calculate lifetime risk of cancer incidence per unit organ/tissue absorbed dose, and using UK estimates of organ/tissue doses from a range of medical procedures, Wall et al. (2011) derived age- and sex-specific risks per unit effective dose for such procedures for the ICRP Euro-American composite population. This comparison involved calculation of risk using information on organ/tissue absorbed doses and organ-/tissue-specific risks as a function of age at exposure and sex for a specified procedure, and expressing the estimated risk per unit effective dose from that procedure. For illustration, a selection of their results for an ICRP Euro-American composite population have been recalculated using the risk data in Table 2.4 of this publication and are presented in Table 5.3. Similarly, using the risk data presented in Table 2.5 for the ICRP Asian composite population, calculated values of age- and sex-specific lifetime risks per Sv are shown in Table 5.4. For males and females and each population, variations in lifetime excess risk per Sv reflect the combination of organ/tissue doses relating to each procedure. A chest x-ray examination, for example, results in doses to a number of organs/tissues, including the liver and stomach, as well as the lungs. Fig. 5.1 presents the data from Table 5.4, together with the lifetime risks per Sv for uniform whole-body irradiation from Table 2.5. For most procedures, the estimates of lifetime excess risk of cancer incidence are within approximately ±50% of those for uniform whole-body irradiation for the particular age at exposure and sex. In considering and comparing these data, it is important to bear in mind the very different doses delivered in the various procedures (see Table 5.1); the results are risk coefficients and illustrate variations in estimated risk per Sv in each case.

(113) It is important that the precision that might be inferred from the values presented in Tables 5.3 and 5.4 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 at exposure and sex differences in

risk estimated for the two composite populations. On the basis of these data, it can be concluded that when considering most x-ray examinations, lifetime risks of cancer incidence per Sv may be around twice as high for exposures at 0–9 years of age than at 30–39 years of age. For patients exposed in their 60s, the estimated lifetime risks are approximately half those for patients in their 30s, falling to less than one-third for patients in their 70s and approximately one-tenth for those in their 80s. Bearing in mind the substantial uncertainties associated with projections of risk to low doses, it is considered reasonable to reflect such variations in possible risk per Sv effective dose in conveying information to clinicians and patients. While health risk assessments using organ/tissue absorbed doses and site-specific risk models represent best use of scientific knowledge, in most circumstances, it will be sufficient to use simple risk terminology as illustrated in Table 5.2. In considering such information, clinicians will wish to take account of factors including the potential benefits of the procedure and the prognosis of the patient's illness.

(114) The use of effective dose to provide an approximate indication of possible lifetime risk of cancer incidence associated with medical procedures is not a substitute for detailed assessments of risk for individuals or specific population groups. Brenner (2008, 2012) proposed the use of an intermediate quantity, termed 'effective risk', in which age-specific tissue weighting factors based on lifetime cancer incidence data replace the age-averaged values used by the Commission in the calculation of effective dose; an example of the use of effective risk for the evaluation of CT examinations is provided by Andrade et al. (2012). While this approach takes direct account of the available data on age specificity of the different cancer types, it may give a spurious sense of accuracy unless associated uncertainties are considered.

(115) A best estimate of risks should be based on measurements or estimates of mean absorbed doses to individual organs/tissues, and use age at exposure 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/tissues. For CT scans, doses per unit doselength product to larger organs and organs 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 that lie near the boundary of the exposed region of the body, as these can vary substantially with small changes in exposure conditions. Patient-specific organ/tissue doses for CT may be calculated from sectional image data for the examination (Li et al., 2011), or adjustments to organ/tissue doses can be made based on patient dimensions or weight (Huda and He, 2012). Uncertainties in both dose and risk estimates should be considered.

Table 5.3. Total lifetime risk of cancer incidence (cases per 100 persons) per Sv effective dose by age at exposure and sex for a range of x-ray examinations, calculated using risk data for the ICRP composite Euro-American population (based on Wall et al., 2011).

| | | Age at exposure (years) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Examination | Sex | 0–9 | 10–19 | 20–29 | 30–39 | 40–49 | 50–59 | 60–69 | 70–79 | 80–89 | 90–99 |
| Cervical spine | M | 13 | 8 | 5 | 3 | 2 | 1 | 0.6 | 0.3 | 0.1 | 0 |
| (AP + Lat) | F | 38 | 18 | 8 | 4 | 2 | 1 | 0.9 | 0.5 | 0.2 | 0 |
| Chest | M | 10 | 8 | 7 | 5 | 5 | 4 | 3 | 2 | 0.7 | 0.1 |
| (PA) | F | 16 | 13 | 11 | 9 | 9 | 8 | 6 | 4 | 2 | 0.3 |
| Thoracic spine | M | 9 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0.6 | 0.1 |
| (AP + Lat) | F | 23 | 16 | 12 | 9 | 8 | 7 | 5 | 3 | 2 | 0.2 |
| Abdomen | M | 14 | 11 | 9 | 6 | 5 | 3 | 2 | 1 | 0.4 | 0.1 |
| (AP) | F | 13 | 10 | 8 | 6 | 5 | 4 | 2 | 2 | 0.7 | 0.1 |
| Pelvis | M | 12 | 9 | 8 | 6 | 4 | 3 | 2 | 1 | 0.4 | 0.1 |
| (AP) | F | 10 | 8 | 6 | 5 | 4 | 3 | 2 | 1 | 0.6 | 0.1 |
| Lumbar spine | M | 13 | 10 | 8 | 6 | 4 | 3 | 2 | 0.8 | 0.3 | 0.1 |
| (AP + Lat) | F | 13 | 10 | 7 | 6 | 4 | 3 | 2 | 1 | 0.6 | 0.1 |
| IVU | M | 14 | 10 | 8 | 6 | 4 | 3 | 2 | 0.9 | 0.3 | 0.1 |
| | F | 13 | 10 | 8 | 6 | 5 | 3 | 2 | 1 | 0.6 | 0.1 |
| Barium swallow | M | 10 | 7 | 5 | 4 | 3 | 2 | 1 | 0.8 | 0.3 | 0.1 |
| | F | 27 | 17 | 11 | 7 | 5 | 4 | 3 | 2 | 0.9 | 0.1 |
| Barium follow | M | 15 | 11 | 9 | 6 | 5 | 3 | 2 | 0.9 | 0.3 | 0.1 |
| | F | 13 | 10 | 8 | 6 | 5 | 3 | 2 | 1 | 0.6 | 0.1 |
| Barium enema | M | 13 | 10 | 8 | 6 | 5 | 3 | 2 | 1 | 0.4 | 0.1 |
| | F | 11 | 8 | 7 | 5 | 4 | 3 | 2 | 1 | 0.6 | 0.1 |
| Coronary | M | 10 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 0.9 | 0.2 |
| angiography | F | 13 | 11 | 10 | 10 | 10 | 9 | 7 | 5 | 3 | 0.3 |
| Femoral | M | 14 | 11 | 8 | 6 | 5 | 3 | 2 | 0.9 | 0.4 | 0.1 |
| angiography | F | 11 | 8 | 7 | 5 | 4 | 3 | 2 | 1 | 0.5 | 0.1 |
| CT head | M | 22 | 15 | 11 | 7 | 5 | 3 | 2 | 0.8 | 0.3 | 0.1 |
| | F | 17 | 12 | 8 | 6 | 4 | 3 | 2 | 0.9 | 0.4 | 0 |
| CT chest | M | 9 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0.5 | 0.1 |
| | F | 22 | 15 | 11 | 9 | 7 | 6 | 5 | 3 | 2 | 0.2 |
| CT abdomen | M | 13 | 10 | 8 | 6 | 4 | 3 | 2 | 0.8 | 0.3 | 0 |
| | F | 13 | 10 | 7 | 6 | 4 | 3 | 2 | 1 | 0.5 | 0.1 |
| CT abdomen + | M | 14 | 11 | 9 | 6 | 5 | 3 | 2 | 0.9 | 0.3 | 0.1 |
| pelvis | F | 13 | 10 | 8 | 6 | 5 | 4 | 2 | 1 | 0.6 | 0.1 |

*(continued on next page)*

Table 5.3. *(continued)*

| | | Age at exposure (years) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Examination | Sex | 0–9 | 10–19 | 20–29 | 30–39 | 40–49 | 50–59 | 60–69 | 70–79 | 80–89 | 90–99 |
| CT chest + | M | 11 | 9 | 7 | 5 | 4 | 3 | 2 | 1 | 0.5 | 0.1 |
| abdomen + pelvis | F | 18 | 13 | 10 | 8 | 6 | 5 | 4 | 2 | 1 | 0.1 |

PA, postero-anterior; AP, anteroposterior; Lat, lateral; IVU, intravenous urogram; CT, computed tomography.
Note that the methodology used in these calculations is based on, but slightly different from, that of ICRP (2007a) (see Section 2.6). Tabulated values are risk coefficients (per Sv) and do not account for the absolute doses delivered in the various procedures.

Table 5.4. Total lifetime risk of cancer incidence (cases per 100 persons) per Sv effective dose by age at exposure and sex for a range of x-ray examinations, calculated using risk data for the ICRP composite Asian population (based on Wall et al., 2011).

| | | Age at exposure (years) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Examination | Sex | 0–9 | 10–19 | 20–29 | 30–39 | 40–49 | 50–59 | 60–69 | 70–79 | 80–89 | 90–99 |
| Cervical spine | M | 10 | 6 | 3 | 2 | 1 | 0.9 | 0.5 | 0.3 | 0.1 | 0 |
| (AP + Lat) | F | 47 | 21 | 10 | 5 | 3 | 1 | 0.8 | 0.4 | 0.2 | 0 |
| Chest | M | 10 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 0.9 | 0.2 |
| (PA) | F | 16 | 12 | 10 | 9 | 8 | 7 | 6 | 4 | 2 | 0.4 |
| Thoracic spine | M | 9 | 7 | 6 | 5 | 4 | 4 | 3 | 2 | 0.7 | 0.1 |
| (AP + Lat) | F | 24 | 16 | 12 | 9 | 8 | 6 | 5 | 3 | 2 | 0.3 |
| Abdomen | M | 14 | 11 | 9 | 7 | 5 | 4 | 2 | 1 | 0.4 | 0.1 |
| (AP) | F | 13 | 10 | 8 | 6 | 5 | 3 | 2 | 1 | 0.6 | 0.1 |
| Pelvis | M | 10 | 8 | 6 | 5 | 4 | 3 | 2 | 0.8 | 0.3 | 0.1 |
| (AP) | F | 8 | 6 | 5 | 4 | 3 | 2 | 2 | 0.9 | 0.4 | 0.1 |
| Lumbar spine | M | 14 | 11 | 9 | 7 | 5 | 3 | 2 | 0.9 | 0.4 | 0.1 |
| (AP + Lat) | F | 13 | 10 | 8 | 6 | 5 | 3 | 2 | 1 | 0.5 | 0.1 |
| IVU | M | 15 | 11 | 9 | 7 | 5 | 4 | 2 | 1 | 0.4 | 0.1 |
| | F | 14 | 11 | 9 | 6 | 5 | 3 | 2 | 1 | 0.5 | 0.1 |
| Barium swallow | M | 10 | 7 | 5 | 4 | 3 | 2 | 2 | 0.9 | 0.4 | 0.1 |
| | F | 31 | 18 | 12 | 8 | 6 | 4 | 3 | 2 | 0.8 | 0.2 |
| Barium follow | M | 14 | 11 | 8 | 6 | 5 | 3 | 2 | 0.9 | 0.4 | 0.1 |

*(continued on next page)*

Table 5.4. *(continued)*

| | | Age at exposure (years) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Examination | Sex | 0–9 | 10–19 | 20–29 | 30–39 | 40–49 | 50–59 | 60–69 | 70–79 | 80–89 | 90–99 |
| | F | 12 | 10 | 8 | 5 | 5 | 3 | 2 | 1 | 0.5 | 0.1 |
| Barium enema | M | 11 | 9 | 7 | 5 | 4 | 3 | 2 | 0.9 | 0.4 | 0.1 |
| | F | 9 | 7 | 6 | 4 | 4 | 3 | 2 | 0.9 | 0.4 | 0.1 |
| Coronary | M | 10 | 8 | 7 | 6 | 6 | 5 | 4 | 2 | 1 | 0.2 |
| angiography | F | 13 | 11 | 10 | 9 | 9 | 8 | 7 | 4 | 2 | 0.5 |
| Femoral | M | 12 | 10 | 7 | 6 | 5 | 3 | 2 | 0.9 | 0.4 | 0.1 |
| angiography | F | 10 | 8 | 6 | 4 | 4 | 3 | 2 | 0.9 | 0.4 | 0.1 |
| CT head | M | 14 | 11 | 7 | 5 | 4 | 3 | 2 | 0.7 | 0.3 | 0.1 |
| | F | 15 | 10 | 7 | 4 | 4 | 3 | 2 | 0.7 | 0.3 | 0.1 |
| CT chest | M | 9 | 8 | 6 | 5 | 4 | 4 | 3 | 1 | 0.6 | 0.1 |
| | F | 22 | 16 | 12 | 9 | 7 | 6 | 4 | 3 | 1 | 0.3 |
| CT abdomen | M | 14 | 11 | 9 | 7 | 5 | 3 | 2 | 0.9 | 0.3 | 0.1 |
| | F | 14 | 10 | 8 | 6 | 5 | 3 | 2 | 1 | 0.5 | 0.1 |
| CT abdomen + | M | 14 | 11 | 9 | 7 | 5 | 3 | 2 | 1 | 0.4 | 0.1 |
| pelvis | F | 13 | 10 | 8 | 6 | 5 | 3 | 2 | 1 | 0.5 | 0.1 |
| CT chest + | M | 11 | 9 | 7 | 6 | 5 | 3 | 2 | 1 | 0.5 | 0.1 |
| abdomen + pelvis | F | 19 | 13 | 10 | 7 | 6 | 5 | 4 | 2 | 1 | 0.2 |

PA, postero-anterior; AP, anteroposterior; Lat, lateral; IVU, intravenous urogram; CT, computed tomography.

Note that the methodology used in these calculations is based on, but slightly different from, that of ICRP (2007a) (see Section 2.6). Tabulated values are risk coefficients (per Sv) and do not account for the absolute doses delivered in the various procedures.

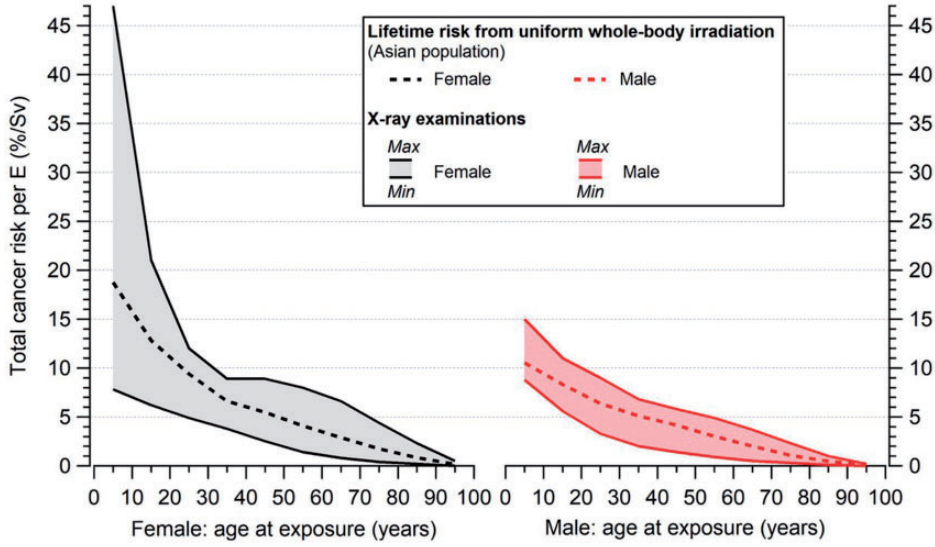


Fig. 5.1. Total lifetime risk of cancer incidence per unit effective dose (cases per 100 persons per Sv: %/Sv) for a composite Asian population as a function of age at exposure and sex for a range of x-ray examinations (Table 5.4) and for uniform whole-body exposure (Table 2.5). Note that the upper and lower curves show the maximum variation in overall lifetime risk per Sv resulting from the various combinations of organ/tissue absorbed doses for the different procedures and the application of organ-/tissue-specific risk models. The dashed lines correspond to uniform whole-body irradiation.

# 6. CONCLUSIONS

(116) This publication provides a review of the use of dose quantities in the system of radiological protection and the scientific basis for the approaches taken. An important aim has been to provide clarity on a number of issues that have caused confusion and some controversy.

(117) A central issue has been the relationship between effective dose and stochastic risks, principally the risk of cancer. It is concluded that effective dose can be used as an 'approximate indicator of possible risk'. This wording was chosen to emphasise the uncertainties inherent in the estimation of risk, and to acknowledge that the doses under consideration are, in many cases, below the levels at which direct epidemiological observations of excess cases of cancer are available. With these caveats, the most straightforward interpretation of the available scientific evidence for the purposes of radiological protection is that a nominal lifetime fatal cancer risk of approximately $5 \times 10^{-2}$ per Sv applies at low doses or low dose rates (i.e. $<10^{-4}$ per mSv). The evidence also shows differences in risk between males and females, and particularly with age at irradiation. Such differences can be taken into account when considering risks to individuals. It is emphasised that situations that require best estimates of risk will be evaluated using best scientific data, including organ/tissue absorbed doses; RBE estimates; and age, sex-, and population-specific risk estimates, with consideration of uncertainties.

(118) Tissue reactions are controlled by setting limits below the threshold doses at which these effects occur. In future, these limits will be set in absorbed dose rather than the current approach of using equivalent dose, which is an intermediate step in the calculation of effective dose. The use of equivalent dose as a protection quantity can be discontinued, simplifying the system. Consideration will need to be given to radiation weighting for tissue reactions.

(119) The tissue weighting factors used in the calculation of effective dose are based on relative detriment values that are averaged over males and females and all ages. Data provided in this publication illustrate the substantial differences observed in the incidence of cancer and in the corresponding estimates of detriment according to age at irradiation, with notable differences between males and females in the age dependence of cancer risk for individual cancer sites. These differences are concealed in the use of age-, sex-, and population-averaged detriment values and a single set of tissue weighting factors. The reasoning has been that the current approach provides a pragmatic, equitable, and workable system in which dose criteria are set and optimisation applied to all workers and all members of the public.

(120) Organ and tissue absorbed doses are now calculated using male and female phantoms of the human body for children of various ages as well as for adults. A consistent approach would be to calculate the corresponding detriment and relative detriment values as well, and calculate effective dose coefficients using these values. Averaging for all workers and all members of the public could then be done as a final stage, or dose criteria could be set with reference to the range of effective dose

coefficients and detriment values presented. This approach would not affect the practical application of the system of protection in general terms, but would facilitate consideration of appropriate protection for population subgroups (e.g. specific consideration of exposures of young children). Further consideration will be given to this topic, and a forthcoming report on detriment calculations will provide more analysis and discussion.

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