# The use of dose quantities in radiological protection

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# The Use of Dose Quantities in Radiological Protection: ICRP Publication 147 Ann ICRP 50(1) 2021

J.D. Harrison[1,2], M. Balonov[3], F. Bochud[4], C.J. Martin[5], H-G. Menzel[6], P. Ortiz-Lopez[7], R. Smith-Bindman[8], J.R. Simmonds[9], R. Wakeford[10,11]

[1] Oxford Brookes University, Faculty of Health and Life Sciences, Oxford, OX3 0BP, UK
[2] Public Health England, Centre for Radiation, Chemical and Environmental Hazards, Didcot, Oxon OX11 0RQ, UK
[5]University of Glasgow, Department of Clinical Physics, Glasgow G12 8QQ, UK

ORCID iDs

J Harrison http://orcid.org/0000-0001-8532-428X

## Abstract

The International Commission on Radiological Protection has published a report (Publication 147) on the use of dose quantities in radiological protection, under the same authorship as this Memorandum. Here, we present a brief and partial summary of the report. ICRP Publication 147 consolidates and clarifies the explanations provided in the 2007 ICRP Recommendations (Publication 103) but reaches conclusions that go beyond those presented in Publication 103. Further guidance is provided on the scientific basis for the control of radiation risks using dose quantities in occupational, public and medical applications. It is emphasised that best estimates of risk to individuals will use organ / tissue absorbed doses and specific dose-risk models. However, 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.

## 1. Introduction

Central to the system of radiological protection are the dose quantities used to set limits to prevent tissue reactions and dose criteria (limits, constraints, reference levels) to optimise protection from stochastic effects. ICRP uses absorbed dose, equivalent dose and effective dose for these purposes as described in the 2007 Recommendations (*Publication 103*; ICRP, 2007) and now in ICRP Publication 147 (ICRP, 2021). ICRP also uses committed dose and collective dose. ICRP provides extensive sets of dose coefficients for circumstances of exposure of workers, public and medical 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. ICRP Publication 147 (ICRP, 2021) provides an explanation of all these quantities in relation to the health effects to which they equate or are intended to control. This Memorandum provides a brief summary of the main issues addressed in ICRP Publication 147.

## 2. Absorbed, equivalent and effective dose

The main dosimetric quantities used in radiological protection are absorbed dose ($D$), with the unit of gray (Gy), and equivalent dose ($H$) and effective dose ($E$), both with the unit of sievert (Sv); the SI base unit is J $kg^{-1}$ in each case. Absorbed dose is calculated for protection purposes as an average over organs and tissues or regions within tissues and is the primary scientific quantity from which $E$ is calculated.

The ICRP protection quantities – equivalent dose ($H$) and effective dose ($E$) – 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 $E$ is in the planning of protection and demonstration of compliance in various situations of exposure of workers and members of the public.

Two risk-adjustment steps are taken in the calculation of $E$ from $D$. Because radiation types differ in their ability to cause biological effects including cancer, calculated values of absorbed dose are multiplied by radiation weighting factors ($w_R$) that take account of the greater effectiveness of densely ionising radiations including alpha particles and neutrons compared to sparsely ionising beta particles and gamma rays. The result is termed equivalent dose, with the unit: sievert (Sv). The final step is to sum the equivalent doses to individual organs and tissues, multiplying each by a tissue weighting factor ($w_T$) 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.

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

where $D_{T,R}$ is absorbed dose from radiation, R, to organ/tissue, T, and $H_T$ is equivalent dose to organ/tissue, T.

## 3. Tissue reactions and absorbed / equivalent doses

Tissue reactions, previously called deterministic effects, result in the impairment of organ/tissue function, observed above dose thresholds, with severity increasing with increasing dose. These high-dose effects include the acute radiation syndromes that may result in irreversible damage to the haemopoietic bone marrow, intestinal tract and brain, but also include direct damage to other organs (ICRP, 2012). Dose limits are set to prevent tissue reactions. Some health effects do not conform precisely to the definition of tissue reactions. In particular, for both cataract formation and circulatory diseases, evidence suggests that lower thresholds of around 0.5 Gy may apply – and data can also be interpreted to suggest non-threshold dose-response relationships (ICRP, 2012; Little et al. 2012; Bouffler et al., 2015).

ICRP Publication 147 (ICRP, 2021) has re-examined the use of dose quantities to set limits to prevent tissue reactions and concluded that absorbed dose should be used for this purpose rather

than equivalent dose. Since equivalent dose is an intermediate step in the calculation of $E$, the $w_R$ values used in its calculation are based on data for the relative biological effectiveness (RBE) of different radiations with a focus on biological end-points relating to stochastic effects rather than tissue reactions. In general, RBE values for tissue reactions tend to be lower than for stochastic end-points.

The proposed change will draw a clear distinction between limits applying to tissue reactions, set in absorbed dose (Gy), and dose criteria 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 anticipated change 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, 2021) for changes to operational quantities (see below). Radiation weighting for tissue reactions will be among the topics given further consideration in preparation for new recommendations.

## 4. Stochastic effects, detriment and effective dose

Cancer is the main risk categorised as stochastic, that is, occurring with a random probability distribution. The principal source of information on risk is 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, 2007; UNSCEAR, 2008; NCRP, 2018). In general, the epidemiological data show a linear dose-response relationship between excess cancer rates and absorbed dose from gamma rays from around 50 - 100 mGy to a few Gy.

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 starting point for the calculations in ICRP Publication 103 (ICRP, 2007) is mainly cancer incidence data from follow-up studies of the Japanese A-bomb survivors. Male and female lifetime excess cancer risks were estimated for a range of organs and tissues, adjusted to low doses and dose rates, and transferred and averaged across a total of seven Asian and Euro-American populations. Further adjustments were made for fatality, morbidity associated with non-fatal cancers, and years of life lost. The cancer detriment values resulting from these calculations and estimated risks of heritable effects from irradiation of the gonads are shown in Table 1. The values shown in the table are calculated as population averages for all ages at exposure and both sexes, with an overall nominal detriment value of $5.7 \times 10^{-2}$ per Sv effective dose. The corresponding value calculated for a working age population (18-64 years of age at exposure) is $4.2 \times 10^{-2}$ per Sv effective dose (ICRP, 2007, 2021). ICRP Publication 103 (2007) also concluded that these values could be approximated by a fatal cancer risk of $5 \times 10^{-2}$ per Sv.

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, as shown in Table 1. $E$ 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 the public, the setting of control criteria (constraints, reference levels and limits), and the demonstration of compliance.

Table 1. Summary of *Publication 103* Nominal Cancer Risks and Detriment for uniform whole-body exposure to gamma rays for the whole population, 0-84 years of age (from Table A.4.1, *Publication 103*, Annex A).

| Tissue | Nominal Risk Coefficient (cases per 10,000 persons per Gy) | Detriment | Relative detriment[+] | Tissue weighting factor, $w_T$ |
|---|---|---|---|---|
| Oesophagus | 15 | 13.1 | 0.023 | 0.04 |
| Stomach | 79 | 67.7 | 0.118 | 0.12 |
| Colon | 65 | 47.9 | 0.083 | 0.12 |
| Liver | 30 | 26.6 | 0.046 | 0.04 |
| Lung | 114 | 90.3 | 0.157 | 0.12 |
| Bone surface | 7 | 5.1 | 0.009 | 0.01 |
| Skin | 1000 | 4.0 | 0.007 | 0.01 |
| Breast | 112 | 79.8 | 0.139 | 0.12 |
| Ovary | 11 | 9.9 | 0.017 | -[a] |
| Bladder | 43 | 16.7 | 0.029 | 0.04 |
| Thyroid | 33 | 12.7 | 0.022 | 0.04 |
| Bone Marrow | 42 | 61.5 | 0.107 | 0.12 |
| Other Solid | 144 | 113.5 | 0.198 | 0.12 |
| Gonads (Heritable) | 20 | 25.4 | 0.044 | 0.08 |
| **Total** | ***1715*** | ***574*** | ***1.000*** | ***1.00***[b] |

[a]Included in $w_T$ for Gonads
[b]Brain and Salivary glands also each assigned $w_T = 0.01$

The use of $E$ requires the assumption of a linear non-threshold (LNT) dose-response relationship at low doses or low dose-rates, and the equivalence of effect of acute and chronic low-level exposures, and of internal and external exposures. Each of these assumptions is considered reasonable in the context of the application of effective dose for protection purposes (ICRP, 2021). The LNT dose-response model is considered to represent a prudent interpretation of current evidence including mechanistic understanding of radiation-induced cancer at low doses or low dose-rates. 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.

Strictly, effective dose applies to the induction of stochastic effects at low doses or low dose-rates. *Publication 103* (ICRP, 2007) 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 above 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 around 1 Sv, but the potential for the occurrence of tissue reactions should be considered. For effective doses up to a few 100s of 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 in excess of 100 mSv (or more precisely, absorbed doses to organs and tissues > 100 mGy of low LET radiation) delivered at high dose rate (> 5 mGy $h^{-1}$), risks will on average be approximately a factor of two greater than implied by ICRP Publication 103 (2007) nominal risk coefficients.

## 5. Reference dosimetric models and dose coefficients

ICRP Publication 103 (2007) introduced the use of reference anatomical models of the human body for the calculation of dose coefficients. The reference adult male and female phantoms being used in current calculations are based on medical imaging data, with the volumes of organs and tissues constituted using voxels (ICRP, 2009). As it is now possible to perform radiation transport calculations without voxelization, ICRP is also developing mesh-type reference phantoms with even greater spatial resolution, enabling the calculation of doses in very small tissue volumes, including single cell layers (ICRP, 2020c). The biokinetics of inhaled and ingested radionuclides are increasingly being modelled to include absorption to blood and the dynamics of recirculation to and from organs and tissues, as well as loss from the body by urinary and faecal excretion (ICRP, 2015; Paquet and Harrison, 2018). These physiologically realistic models can be used for the interpretation of bioassay measurements as well as the calculation of integrated retention of radionuclides in organs and tissues and consequent doses.

The use of male and female reference phantoms, to replace the previously used hermaphrodite phantoms, requires sex-averaging in the calculation of effective dose. Thus, absorbed doses and equivalent dose to organs and tissues are calculated separately for males and females and averaged in the calculation of effective dose to the sex-averaged reference person. ICRP has developed a set of reference phantoms for children of different ages (ICRP, 2020a) as well as for adults and will also provide reference phantoms for the pregnant woman and fetus.

ICRP Publication 116 (ICRP, 2010a) provided the first set of dose coefficients calculated using Publication 103 (ICRP, 2007) methodology and reference anatomical models (ICRP, 2009), considering occupational exposures to external radiation. The radiations considered are monoenergetic photons; electrons and positrons; neutrons; protons; pions (negative/positive); muons (negative/positive) and helium ions. Comparisons of the protection quantities, equivalent and effective dose, with corresponding operational quantities (see below) showed the latter to provide conservative estimates of dose in the majority of cases.

ICRP Publications 130, 134, 137 and 141 (ICRP, 2015, 2016, 2017b, 2019) provide methodology and updated dose coefficients and bioassay data for internal exposures of workers following the inhalation or ingestion of radionuclides. The final report in this series is in preparation. Work is also in progress on replacement dose coefficients for radionuclide intakes by members of the public and for radiopharmaceutical administrations to patients. For the first time, ICRP has published dose coefficients for exposures of members of the public, including children, to external sources (ICRP, 2020b) and a further report is in preparation to provide reference dose coefficients for medical diagnostic X-ray examinations.

The dose coefficient datasets provided by ICRP generally include values for exposure or intake for equivalent dose to organs and tissues and effective dose. Tabulated values in the published reports are accompanied by more extensive data compilations in data-viewers available on the ICRP website: www.ICRP.org. 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.

Dose criteria (limits, constraints, reference levels) are generally set in terms of annual exposures. In evaluating annual exposures, $E$ 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 to age 70 years for children. Radionuclides with long physical half-lives and long biological half-times of retention in organs and tissues may continue to deliver doses to body tissues over many years after intake. For plutonium-239, for example, effective dose in the first year after intake will be generally less than 10% of the total committed effective dose. For most radionuclides, however, this effect will be much less significant and for many, including iodine-131 and caesium-137, dose will be delivered entirely or very largely in the year of intake. For practical purposes, the use of committed dose ensures that longer term exposures from intakes of radionuclides are taken into account.

Although effective dose coefficients are provided for a number of age groups of children, it is normally sufficient in public dose assessments to consider only the age-groups of 1 year and 10 years, together with adults (ICRP, 2006, 2021). 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; specifically for phosphorus isotopes, calcium-45 and strontium-89, the fetus/breast-fed infant may receive significantly higher doses than other age groups in some exposure situations.

## 6. Collective dose

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 (eg. UNSCEAR, 2008; NCRP, 2019).

The use of collective dose 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 (ICRP, 2021). The computation of numbers of cases of cancer based on collective effective doses involving extremely low exposures to very large populations should be avoided. Because of the large uncertainties associated with such estimates, the results will be more misleading than informative. ICRP Publication 101 (ICRP, 2006) gives advice on the use of collective dose as a tool for optimisation of protection, 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.

## 7. Operational quantities

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 as used to calculate dose coefficients (ICRP, 2015). For the monitoring of external exposures, operational dose equivalent quantities for area and individual monitoring have been defined by ICRU (1985, 1988, 1993, 2021). 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 eye lens and skin.

The set of ICRU operational dose quantities in current use was defined more than 30 years ago. Following from ICRP Publication 116 (2010a), which provided updated dose coefficients for occupational exposures to external sources using the reference adult phantoms (see above), ICRU (2021) 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. ICRU (2021) propose changes to the 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 ICRP Publication 116. As a consequence, these operational quantities, renamed personal dose, $H_p$, and ambient dose, $H^*$. will be implicitly defined in the reference anthropomorphic phantoms, resulting in improved coherence and simplification of the system. Furthermore, the operational quantities for measurement of eye and skin doses will become absorbed dose quantities, consistent with the change proposed in ICRP Publication 147 (2021) to use absorbed dose instead of equivalent dose to set limits to prevent tissue reactions. The expectation is that these changes will be introduced after new ICRP recommendations.

## 8. Age and sex specific cancer risks

The nominal risk and detriment coefficients given in ICRP Publication 103 (2007) are age-, sex- and population- averaged values, except for the distinction between the whole population (0 – 84 years of age at exposure) and the working age population (18 - 64 years of age at exposure), with values of $5.7 \times 10^{-2}$ per Sv and $4.2 \times 10^{-2}$ per Sv, respectively.

Table 2 is taken from ICRP Publication 147 (2021) and shows an example of lifetime cancer risks calculated separately for males and females and different ages at exposure. The methodology used was as presented by Wall et al (2011) , calculating cumulative risks of cancer incidence per unit organ/tissue absorbed dose (Gy) up to an attained age of 100 years separately for males and females and by category of age at exposure for different cancer types. Risk models were derived from the A-bomb survivor cohort (Preston et al. 2007), using ICRP Publication 103 (2007) methodology. To define baseline incidence rates, Wall et al. (2011) used ICRP Publication 103 values for a Euro-American composite population. The values given in ICRP Publication 147 (2021) and presented in Table 2 are calculated as Lifetime Attributable Risk (LAR) rather than Risk of Exposure-Induced Cancer (REIC) as in Wall et al. (2011) but the results are similar. ICRP Publication 147 (2021) also presented results obtained using baseline incidence rates for the ICRP Asian composite population, again with similar results to those shown in Table 2.

As illustrated in Table 2, there is a clear effect of age at exposure on cancer risks, with overall risks compared to those in the 30–39 years age group being about double in the youngest group (0–9 years at exposure) and about half by age 60–69 year at exposure. However, the data also show substantial differences between cancer types in variations in risk with age at exposure,

and the contribution of the different cancer types to overall lifetime risk varies substantially with sex and age at exposure.

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].

Table 2. 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 (2007) Euro-American composite population (from ICRP Publication 147, 2021).

| | 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 EAR and ERR models and applying a DDREF 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 (2003) was used for breast cancer. Minimum latency periods applied were 2 years for leukaemia and 5 years for solid cancers.

## 9. Medical exposures, effective dose and risks

While the use of *E* for optimisation of protection of works and members of the public is well-established and conforms to international standards, the use of *E* in assessing doses to medical

patents is different and provokes much discussion. The radiation doses received by patients in diagnostic and interventional procedures are recorded in terms of quantities that can be measured for each technique. Surveys are made to establish diagnostic reference levels (DRLs) in terms of these measurable quantities (ICRP, 2017a). However, the use of such data is limited in application and *E* is used for comparisons of doses from different diagnostic and interventional imaging modalities (e.g. CT and nuclear medicine) and exposure techniques that give different spatial distributions of radiation within the body tissues. In this context, *E* 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. *E* 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, *E* provides an approximate measure of possible detriment. Thus, *E* 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.

Table 3. 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[a] (ICRP, 2021).

| **Effective dose (mSv)** | **Risk of cancer** | **Proposed term for dose level** | **Examples of medical radiation procedures within different dose categories[c]** |
|---|---|---|---|
| < 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 and $^{99m}$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[b] | 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><br>Renal/visceral angioplasty, Iliac angioplasty, follow-up of endovascular aneurysm repair. (35-100 mSv). |
| 100s | >$10^{-2}$ based on epidemiology[b] | Moderate | Multiple procedures and follow-up studies. |

[a]Martin, 2007; Wall et al., 2011; Martin and Sutton, 2014.

[b]Risk bands are lifetime detriment adjusted cancer incidence to nearest order of magnitude.

[c]Effective doses based on UK data for diagnostic procedures and ICRP (2010b) for interventional radiology.

Table 3 is reproduced from ICRP Publication 147 (2021) and shows a scale linked to effective dose from medical diagnostic x-ray procedures, 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 of 1 mSv and greater 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 to 100 mSv can be termed low in this specific context, while that for effective doses in the range of 1 mSv to 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 less than 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.

## 10. Conclusions

ICRP Publication 147 (2021) 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.

An important issue is the relationship between effective dose and stochastic risks, principally the risk of cancer. ICRP (2021) concludes 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 about $5 \times 10^{-2}$ per Sv applies at low doses or low dose-rates; that is $< 10^{-4}$ 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. ICRP emphasise 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.

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.

The tissue weighting factors used in the calculation of effective dose are based on relative detriment values that are averages over males and females and all ages. Data provided in this report illustrate the substantial differences observed in cancer incidence 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.

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 last 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 sub-groups, for example, specific consideration of exposures of young children.

ICRP is now engaged in a review of the system of radiological protection, aiming towards development of the next fundamental recommendations of ICRP with a time-scale of around 10 years. Several task groups have been established or are being considered on topics including the updating of cancer risk models, calculation of detriment, determination of DDREF, integration of heritable effects and cardiovascular disease risks, and radiation weighting for tissue reactions and stochastic effects. The work of these groups will underpin changes introduced in new recommendations. ICRP Publication 147 (2021) is part of this programme.

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