Journal of Radiological Protection

Official journal of the Society for Radiological Protection

ACCEPTED MANUSCRIPT

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To cite this article before publication: John D Harrison *et al* 2021 *J. Radiol. Prot.* in press https://doi.org/10.1088/1361-6498/abe548

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

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Abstract

The International Commission on Radiological Protection has recently published a report (ICRP Publication 147; 2021) on the use of dose quantities in radiological protection, under the same authorship as this Memorandum. Here, we present a brief summary of the main elements 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, appropriate relative biological effectiveness factors and dose-risk models for specific health effects. However, bearing in mind uncertainties including those associated with risk projection to low doses or low dose rates, it is concluded that in the context of radiological protection, effective dose may be considered as an approximate indicator of possible risk of stochastic health effects following low-level exposure to ionising radiation. In this respect, it should also be recognised that lifetime cancer risks vary with age at exposure, sex and

population group. The ICRP report also concludes that equivalent dose is not needed as a protection quantity. Dose limits for the avoidance of tissue reactions for the skin, hands and feet, and lens of the eye will be more appropriately 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. The International Commission on Radiological Protection uses absorbed dose, equivalent dose and effective dose for these purposes as described in the 2007 ICRP 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 patients. The International Commission on Radiation Units and Measurements (ICRU) has defined operational quantities for occupational exposures to external sources of radiation 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 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.

Effective dose (E) is the main ICRP protection quantity, allowing the weighted summation of doses from all sources of exposure, external and internal, as a single number that can be compared with dose criteria (limits, constraints and reference levels) that relate to potential stochastic effects (cancer and heritable effects) from uniform whole-body radiation exposure.

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 organ/tissue absorbed dose are multiplied by radiation weighting factors (w_R) that take account of the relative biological effectiveness (RBE) of densely ionising radiations including alpha particles and neutrons compared to sparsely ionising beta particles and gamma rays. The result is termed organ/tissue equivalent dose (H), with the unit, sievert (Sv). The final step is to calculate the weighted sum of the equivalent doses to individual organs and tissues, multiplying each by a tissue weighting factor (w_T) that approximates its relative contribution to the overall detriment from uniform whole-body irradiation by sparsely ionising radiation. Thus, effective dose is a doubly-weighted average of organ/tissue absorbed doses and risk per unit effective dose is intended to be comparable irrespective of the radiation type and distribution of organ/tissue doses. Thus,

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

where $D_{T,R}$ is absorbed dose from radiation type, R, to the specific 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 specific 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 central nervous system, 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 ocular cataract formation and diseases of the circulatory system, evidence suggests that lower thresholds may apply than discussed in Publication 103 (ICRP, 2007), with values of around 0.5 Gy in each case (ICRP, 2012), 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 effective dose, the w_R values used in its calculation are based on data for the relative biological effectiveness (RBE) of different radiations for 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 clarify the distinction between dose limits to avoid tissue reactions, set in absorbed dose (Gy), and dose criteria for limitation and optimisation of protection against stochastic effects, set in effective dose (Sv). ICRP proposes to make this change as an element of the considerations in the next general recommendations. It is consistent with the approach taken by the US National Council on Radiation Protection and Measurements in recommendations for the USA (NCRP, 2018) and proposed changes to operational quantities (see below) developed by the International Commission on Radiation Units and Measurements (ICRU, 2021). Radiation weighting factors for tissue reactions will be among the topics given further consideration in preparation for new ICRP recommendations.

4. Stochastic effects, detriment and effective dose

Cancer is the main risk categorised as stochastic, that is, occurring with a random probability distribution for an exposed group with defined characteristics. Epidemiological studies of the Japanese survivors of the atomic bombings at Hiroshima and Nagasaki in 1945 provide most data, but studies of occupational exposures are also increasingly providing important results (ICRP, 2007; UNSCEAR, 2008; NCRP, 2018). In general, the epidemiological data show an approximately 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 an ICRP construct used as a measure of the harmful effects on health of radiation exposures at low dose and dose rates. 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, both absolute and relative, 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 composite 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. These values were calculated as population averages for all ages at exposure and both sexes, with an overall nominal detriment value of 5.7×10^{-2} per Sv effective dose. The corresponding value calculated for a working age population (18-64 years of age at exposure) is 4.2×10^{-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 5×10^{-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 overall detriment, as shown in Table 1. *E* is the central radiological protection quantity used internationally in the assessment and control of low-level exposures from external and internal sources.

Table 1. Summary of *ICRP 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, to permit the direct addition of doses, the equivalence of effect of acute and chronic low-level exposures, and of internal and external exposures (suitably weighted as appropriate). Each of these assumptions is considered

reasonable in the context of the application of effective dose for protection purposes (ICRP, 2021). The LNT model is generally agreed to be a prudent interpretation of current evidence, including understanding of mechanisms of radiation interactions at low doses or low dose-rates. In a review of epidemiological studies, NCRP (2018) concluded that no other model represents a more pragmatic or prudent interpretation for radiological protection purposes.

Strictly, effective dose is intended to be applied at low doses and low dose-rates. However, effective doses greater than 100 mSv may need to be considered in particular circumstances, such as the short-term relaxation of worker doses in order to regain control in an accident. ICRP Publication 147 (2021) concludes that effective dose could be used up to around 1 Sv, but the potential for tissue reactions should be considered if exposures could be significantly non-uniform, with substantially higher doses to some organs / tissues. It should also be noted that for effective doses greater than 100 mSv (absorbed doses to organs / tissues > 100 mGy, low LET) at high dose rate (> 5 mGy h^{-1}), risks will on average be approximately twice the values given as nominal risk coefficients in ICRP Publication 103 (2007).

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 the resultant doses.

With the introduction of reference phantoms, absorbed and equivalent doses to organs and tissues are calculated separately for males and females and averaged in the calculation of effective dose to the Reference Person. Reference phantoms have now also been developed for children of different ages (ICRP, 2020a) and work is in progress on reference phantoms of 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. ICRP Publications 130, 134, 137 and 141 (ICRP, 2015, 2016, 2017b, 2019) provide Publication 103 (ICRP, 2007) compliant 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 well-advanced on corresponding sets of 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 to external radiation 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/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 frequently set in terms of annual exposures. 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 to age 70 years for children. Radionuclides with long physical half-lives and long biological half-times of retention in organs and tissues will deliver doses to body tissues over many years after intake. For the example of plutonium-239, effective dose in the first year after intake is generally less than 10% of the total committed effective dose. However, for many radionuclides, including iodine-131 and caesium-137, dose will be confined entirely or very largely to the year of intake.

While effective dose coefficients are given for five age groups of children (3 months, 1, 5, 10 and 15 years) as well as adults, dose assessments for public exposures generally only require consideration of the age-groups of 1 year and 10 years, together with adults (ICRP, 2006, 2021). For intakes of radionuclides, effective dose coefficients are provided for the fetus for comparison with values for other age groups, indicating that it is only in the case of a few radionuclides that fetal doses will be greater than doses for other age groups; specifically for phosphorus isotopes, calcium-45 and strontium-89. However, fetal doses may exceed maternal doses for a number of other radionuclides, notably including doses resulting from the transfer of iodine isotopes to the fetal thyroid in late gestation.

6. Collective dose

Collective effective dose has important applications in the optimisation of protection of workers and the public. Combined with information on the distribution of individual doses, it can help determine the optimum balance between larger exposures of a few workers and smaller exposures of a larger number of workers. Collective dose has also been widely used to compare exposure levels in different countries and changes in exposures over time, considering occupational, public and medical exposures (e.g., UNSCEAR, 2008; NCRP, 2019).

Collective dose may provide useful input to the prediction of possible health effects in some circumstances; for example, for initial assessments of the value of or need for epidemiological or medical follow-up. However, estimates of health effects should be compared with background morbidity rates, with account taken of distribution over time and space, and uncertainties in dose and risk estimation (ICRP, 2021). The calculation of cancer cases over large populations exposed to very low doses will not be informative because of the large uncertainties involved.

7. Operational quantities

Doses to workers from intakes of radionuclides can be assessed by direct methods that include external whole-body and organ monitoring and indirect methods that include measurement of urinary excretion, applying the same biokinetic models as used to calculate dose coefficients

(ICRP, 2015). Doses to workers from external exposures are measured using operational dose quantities for area and individual monitoring (ICRU, 1985, 1988, 1993). Monitoring instruments are calibrated in terms of these quantities. The measurements made are recorded as estimates of effective dose, and equivalent doses to the eye lens and skin.

The ICRU operational quantities were defined in the 1980s and have now been reviewed (ICRU, 2020) with particular reference to ICRP Publication 116 (2010a), which provided Publication 103 (ICRP, 2007) dose coefficients for occupational exposures to external sources using the reference adult phantoms (see Section 5). It was concluded that the current methodology should be replaced with a simpler scheme in which the reference adult phantoms (ICRP, 2009), adopted jointly by ICRP and ICRU, are used to calculate the dose coefficients for both the operational and protection quantities. This change will ensure that the operational quantities provide a good measure of the protection quantities across the energy range. Thus, personal dose equivalent, $H_p(10)$, and ambient dose equivalent, $H^*(10)$, will be replaced by personal dose, H_p, and ambient dose, H^*,and redefined as the product of fluence or air kerma and dose coefficients derived from the maximum of the dose coefficient curves for effective dose as a function of particle energy in ICRP Publication 116 (2010a). In addition, the operational quantities for the lens of the eye and skin will be defined in absorbed dose with the unit gray, 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. It is expected that the practical implementation of the new definitions of operational quantities will take place after new ICRP general recommendations are issued.

8. Age- and sex-specific cancer risks

Section 4 presented a brief summary of the methodology used in ICRP Publication 103 (2007) to calculate age-, sex- and population- averaged stochastic detriment, with an overall value for the whole population (0 – 84 years of age at exposure) of 5.7×10^{-2} per Sv and a lower value of calculation of 4.2×10^{-2} per Sv for a working age population (18 - 64 years of age at exposure).

Table 2 is taken from ICRP Publication 147 (2021) and shows an example of lifetime excess cancer risks calculated separately for males and females and different ages at exposure for a Euro-American composite population. The methodology used was as presented by Wall et al (2011) , calculating cumulative risks of cancer incidence per unit organ / tissue absorbed dose (Gy) for different cancer types, to an attained age of 100 years by category of age at exposure, and separately for males and females. Risk models were as used in ICRP Publication 103 (2007), with baseline incidence rates for the ICRP Euro-American composite population. The values given in ICRP Publication 147 (2021) and presented in Table 2 are calculated as Lifetime Attributable Risk (LAR), not 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 are clear effects of sex and age at exposure on cancer risks, with overall risks when compared to those in the 30–39 years age group, being about 2 – 3 times greater in the youngest group (0–9 years at exposure) and about 2 – 3 times lower 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 with age at exposure. For the example of thyroid cancer, risks are a factor of about 5 times higher for exposures of young girls (0 – 9 years) than young boys and for both females and males, risks at the youngest ages are more than 10 times greater than exposures at 30 – 39 years. Differences in thyroid doses and risks for intakes of iodine isotopes were considered by Puncher et al. (2017).

It would have been possible for ICRP Publication 103 (2007) to present detriment values separately for males and females of different ages, resulting in a similar pattern of differences to that shown in Table 2. However, since protection criteria are set for all members of the public and for all workers, the requirement was for sex- and population- averaged values of detriment. Although there are considerable uncertainties associated with the derivation of risk estimates and their application to low doses and low dose-rates (NCRP, 2012; UNSCEAR, 2012b), it will be instructive to be aware of the underlying differences in risk illustrated in this section when applying the system, so that appropriate protection can be ensured.

Table 2. Estimates of lifetime attributable risks of cancer incidence per absorbed dose (cases per 100 per Gy) from uniform whole-body 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 effective dose for optimisation of protection of workers and members of the public is well-established and conforms to international standards, the use of effective dose in assessing doses to medical patients 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 effective dose 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 between

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). 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.

body organs and tissues. 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 applications, effective dose provides an approximate measure of possible detriment. Thus, effective dose is 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 is reproduced from ICRP Publication 147 (2021) and provides a categorisation of effective doses and risks from medical diagnostic x-ray procedures. The terms used for effective doses of 1 mSv and greater are the same as applied by UNSCEAR (2012a) to uniform whole-body absorbed doses from gamma radiation (mGy) in the same ranges. Thus, for example, the inferred risk from effective doses of 1 to 10 mSv are termed very low in this context.

10. Conclusions

ICRP Publication 147 (2021) provides a review of the use of dose quantities in the system of radiological protection recommended by ICRP, 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 term is intended to underline the uncertainties in the estimation of risk at low doses and to recognise that these doses are very often below levels at which excess cancer rates have been demonstrated in epidemiological studies. However, the prudent conclusion from the available scientific evidence for the purposes of radiological protection is that a nominal lifetime fatal cancer risk of about 5×10^{-2} per Sv applies at low doses or low dose-rates; that is $< 10^{-4}$ per mSv. The epidemiological evidence also shows differences in risk between males and females and particularly with age at irradiation. These differences can be taken into account when considering risks to individuals. ICRP (2021) emphasises that best estimates of risk should be calculated using 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. ICRP (2021) concludes that these limits will be more appropriately set in terms of absorbed dose rather than the current approach of using equivalent dose, which is an intermediate step in the calculation of effective dose. ICRU (2020) proposes a parallel change in the operational quantities used as measures of exposures of the lens of the eye and skin. The intention is that changes to both the protection and operational quantities will be introduced at the time of the next ICRP general recommendations. A review of radiation weighting factors is planned, distinguishing values for tissue reactions and stochastic effects.

The tissue weighting factors used in the calculation of effective dose are based on detriment values that are averaged for males and females and all ages. Data provided by ICRP (2021) and in shortened version here illustrate the substantial differences observed in cancer incidence according to age at irradiation, with notable differences between males and females in the age-dependence of cancer risk for individual cancer sites. Such 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.

Since effective dose is calculated using dosimetric phantoms of the human body for males and females of ages, 3 months, 1, 5, 10, 15 and 20 years of age, it would be possible to calculate cancer risks and detriment (or some similar measure) separately each of these ages, and also for older age groups. Values would be derived for absolute and relative detriment for males and females separately at each age at exposure. It might then be most appropriate and informative to calculate effective dose separately for males and females of the various ages using relative detriment for tissue weighting. Such changes would represent best use of the available scientific evidence and avoid the criticism that women and children are not adequately protected. It would be clear that the inferred risk associated with, for example, a 5 mSv reference level would be different depending on the age and sex of the exposed individuals. The corollary should then be that optimisation is applied with a clear understanding of possible risks in the situation being considered. 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 to radioisotopes of iodine.

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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