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MEMORANDUM

Low doses of ionising radiation: definitions and contexts

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Abstract

The term 'low dose' is applied to different levels of dose depending on the circumstances of exposure, with the potential for confusion unless the reasoning is clear. The United Nations Scientific Committee on the Effects of Ionising Radiation has defined low absorbed doses of ionising radiation as below about 100 mGy, and low dose rates as below 0.1 mGy min^{-1} (6 mGy h^{-1}). These values relate to the interpretation of scientific evidence from epidemiological and biological studies. The International Commission on Radiological Protection has used similar values of 100 mSv and 5 mSv h^{-1} and applied this categorisation directly to the specific situation of patients undergoing diagnostic procedures: doses below 100 mSv were referred to as 'low' and doses below 10 mSv as 'very low'. Consideration of other exposure situations suggest that the same terms can be used for exposures received by emergency workers. However, for workers and members of the public in planned exposure situations, it is suggested that the term 'low dose' applies to doses below 10 mSv and 1 mSv, respectively—that is, below the dose limits. In each case, dose is being used as a surrogate for risk—risks at low doses are uncertain and estimates may change, but order of magnitude considerations are sufficient in most cases. Doses of < 100 mSv, < 10 mSv and < 1 mSv correspond to life-time cancer risk estimates of the order of $< 10^{-2}$, $< 10^{-3}$ and $< 10^{-4}$, respectively.

1. Introduction

The UK Government Committee on Medical Aspects of Radiation in the Environment (COMARE), sponsored by the Department of Health and Social Care, has a remit to advise on health effects of radiation exposures. Members have identified a need for clarity on definitions of what constitutes a low dose of radiation, noting that the term is used differently according to context. This note was prepared as a COMARE information paper to encourage a more coherent and consistent use of descriptors when communicating the significance of given levels of exposure in different circumstances.

The United Nations Scientific Committee on the Effects of Ionising Radiation (UNSCEAR 2012) has defined low absorbed doses of ionising radiation as below about 100 mGy, and low dose rates as below 0.1 mGy min^{-1} (6 mGy h^{-1}). ICRP (2021) has similarly referred to effective doses below 100 mSv as low, and also to high dose rates being greater than 5 mSv h^{-1}. While these similar classifications of low doses and low dose rates are valid scientifically and may apply directly in particular circumstances, they can create confusion when considering a range of exposure situations.

ICRP (2007) characterises exposure situations as: planned, existing and emergency. Separate consideration is also given to exposures received by workers, the public and medical patients. For planned exposures of members of the public, there is a dose limit of 1 mSv y^{-1} and constraints will be applied to keep

Table 1. Terminology for bands of radiation dose (from UNSCEAR 2012).

Terminology for dose bands	Range of absorbed dose for low-LET radiation	Scenarios
High	Greater than about 1 Gy	Typical dose (whole or partial body) to individuals after severe radiation accidents or from radiotherapy
Moderate	About 100 mGy to about 1 Gy	Doses to about 100 000 of the recovery operation workers after the Chernobyl accident
Low	About 10 to about 100 mGy	Dose to an individual from multiple whole-body CT scans
Very low	Less than 10 mGy	Dose to an individual from conventional radiology (without CT or fluoroscopy)

doses to a fraction of 1 mSv y^{-1}. It can be difficult for both radiation protection practitioners and stakeholders to understand why doses should be kept so low when 100 mSv has also been regarded as low. In addition, levels of radioactivity may be referred to as 'high' while resulting in very low doses. For example, Public Health England (PHE 2021) has advised that land is considered to have a high level of radioactive contamination when the resulting effective dose to a person using the land is greater than 3 mSv y^{-1}. Other examples of conflicting and potentially confusing variations in terminology are discussed elsewhere (Smith and Thorne 2016, Smith and Martinez 2017).

The sections below provide further explanation of definitions of low doses, the associated risks, and the context of differences in exposure situations. Comparisons are drawn to illustrate how terminology may be used differently depending on the circumstances of exposure.

2. Descriptions of dose levels

Table 1 shows terminology used by UNSCEAR (2012) to describe dose bands, principally in relation to the interpretation of epidemiological data, referring to absorbed dose (Gy) to the whole body or to a specific organ or tissue of an individual, from sparsely ionising, low LET radiation (gamma rays, x-rays, beta particles). For densely ionising, high LET radiations (alpha particles, neutrons), mention is made of the need to make adjustment to absorbed dose to take account of increased effectiveness per Gy in causing health effects, but no comment is made on whether this would affect dose banding.

In considering low doses and cancer risks, ICRP (2005) classified dose levels as follows: 'As a rough rule of thumb, effective doses of the order of 1 Sv, 100 mSv, 10 mSv, 1 mSv and 0.1 mSv may be called 'moderately high', 'moderate', 'low', 'very low' and 'extremely low', respectively. However, in common usage 'low' and 'high' are usually relative terms, i.e. short-hand for 'relatively low' and 'relatively high', which may refer to ranges of different numerical values depending on context.'

Table 2 shows ICRP (2021) dose ranges and proposed descriptors for the specific situation of exposure of patients in medical diagnostic procedures. Paralleling the UNSCEAR (2012) scheme, doses below 100 mSv are 'low' and those below 10 mSv are 'very low'. Table 2 includes estimates of life-time cancer risk alongside the dose bands, because it is primarily risk that is being described as low—or very low—dose is being used here and elsewhere as a surrogate for risk.

In estimating risk to health, dose rate is also considered. In the context of the application of epidemiological data to exposures at low doses and low dose rates, ICRP (1991) chose values of 0.2 Gy and 0.1 Gy h^{-1} as the boundary between high and low. Muirhead *et al* (1993) of the then National Radiological Protection Board used more conservative values of 0.1 Gy and 0.1 mGy min^{-1}. The NRPB values have since been adopted by UNSCEAR (2012) and similarly by ICRP (2021) as 100 mSv and 5 mSv h^{-1}.

In addition to the categorisation of levels of dose and dose rate in relation to epidemiological observations of health, UNSCEAR (1993, 2000) has previously discussed categorisation based on biophysical considerations and cellular and animal data. For low LET radiation, and the example of ^{60}Co γ-rays and an 8 μm spherical cell (or nucleus), there is an average of one track per cell (or nucleus) when the absorbed dose to the cell population is about 1 mGy. With the number of interacting tracks following a Poisson distribution, a dose of 0.2 mGy or below would correspond to having fewer than 2% of the cells receiving more than one track and changing the dose will essentially just change the fraction of cells affected i.e. the dose-effect should be linear. Such doses could be classified as low on the basis that dose-response can be expected to be linear

Table 2. 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] (from ICRP 2021).

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

[a] Martin (2007), Wall *et al* (2011), Martin and Sutton (2014).
[b] Effective doses based on UK data for diagnostic procedures and ICRP (2010) for interventional radiology.
[c] Risk bands are lifetime detriment adjusted cancer incidence to nearest order of magnitude.
[d] 100–1000 mSv, consistent with table 1.

without any effect of dose rate. A further alternative is that the low dose region can be determined using the dose-response relationship for cellular effects in which the incidence I of the effect at dose D is

$$I(D) = \alpha D + \beta D^2$$

where α and β are the coefficients for the linear and quadratic terms of the fitted dose response. For example, for unstable chromosome aberrations in lymphocytes the α/β ratio is about 200 mGy and so the response is

essentially linear up to 20 mGy (UNSCEAR 1993, 2000). This definition of low dose as a few 10 s mGy is supported by animal data.

3. Epidemiological data and risk estimates

As reviewed recently by Laurier *et al* (2023), there is good evidence from epidemiological studies of excess solid cancer and leukaemia at doses above about 50–100 mSv. The most informative studies have been those of the Japanese A-bomb survivors, but studies of radiation workers are also now providing broadly consistent results in terms of overall risk estimates, despite the very different dose rates involved (Laurier *et al* 2023, Richardson *et al* 2023). However, it should be noted that difficulties have been identified in the interpretation of the worker studies (e.g. Wakeford 2023a, 2023b, 2024) and types of solid cancer identified as being increased by radiation show notable differences (Laurier *et al* 2023).

The epidemiological data are consistent with and support the use of a linear non-threshold (LNT) model of dose-response for cancer induction by radiation at low doses and low dose rates (Laurier *et al* 2023, Wakeford *et al* 2023). However, there is not, and there is unlikely to be, direct evidence of effects at doses of the order of 10 mSv and below because of the limitations imposed by statistical uncertainties in identifying possible small excesses of disease above background levels. Reliance is then placed on biological data which largely supports the use of a LNT dose-response model, particularly considering the central role of stable chromosomal mutations in early carcinogenesis (UNSCEAR 2021, Laurier *et al* 2023). The international consensus is that the epidemiological and biological evidence considered together provide strong support for the use of the LNT model for radiological protection purposes. Nevertheless, uncertainties in low dose risk should be recognised—risks at very low doses and below in table 2 from ICRP are referred to as 'inferred', consistent with discussions of attributability of risk by UNSCEAR (2012).

ICRP (2007) currently applies a dose and dose rate effectiveness factor (DDREF) of two in applying risk estimates for solid cancer derived from the A-bomb studies to exposures at low doses and low dose rates. Higher effectiveness of low LET radiation delivered at high doses and dose rates is considered to reflect the decreasing distance between sites of DNA damage caused by multiple track traversals, resulting in greater mis-repair. At low doses, track interactions do not make a significant contribution to DNA damage resulting from mis-repair due to increased distance between lesions and/or, at low dose rates, there is time for DNA repair (or mis-repair) of one lesion before a second traversal. Animal data have been interpreted to support the use of a DDREF of two or greater (Hoel *et al* 2018). On this basis, a difference would be expected between the risk estimates derived from studies of the A-bomb survivors and of nuclear workers (Hoel 2018, Wakeford 2021). Studies of Mayak workers (Russian Federation) do appear to support the use of a DDREF—of two (Hoel *et al* 2018, Wakeford 2021). In contrast, recent international poolings of worker studies (UK, France and USA) do not support the use of a DDREF (Richardson *et al* 2023) and, indeed, the results can be taken to suggest higher risks per Sv than obtained from the A-bomb survivor studies. However, it would seem premature to reach conclusions on the basis of these data until anomalous patterns of risk are resolved. Particularly problematical are observations of higher risks per Sv for workers employed after 1957 with lower overall doses when compared with all workers, and greater risks (per Sv external dose) for workers monitored only for external exposures when compared with those also flagged for possible internal exposures (Wakeford 2024). Separate analyses for US and UK workers show that the former were responsible for the marked differences in risk in relation to employment history and the latter, and particularly Sellafield workers, for the differences in relation to monitoring for internal exposures (Gillies and Haylock 2014, Kelly-Reif *et al* 2023, Hunter and Haylock 2024). On-going studies in the US are bringing together a large number of cohorts of nuclear workers in the Million Person Study, paying particular attention to the accuracy of dose estimates, and may help clarify this confusing picture of risk to radiation workers (Boice *et al* 2022). ICRP has a task group considering the accumulating evidence on risks at low doses and the use of DDREF.

For radiological protection purposes, ICRP (2007) used cancer risk data mainly from the A-bomb survivor studies to estimate lifetime risks averaged over several populations from around the world. From cancer incidence data, 'detriment' coefficients (risk per Sv) were derived that take account of fatality, morbidity and years of life lost. A DDREF of two was used for solid cancers and a linear-quadratic dose-response was applied for leukaemia. A component for hereditary effects was added, although no significant effects have been seen in epidemiological studies, because biological data and mechanistic considerations support their inclusion. However, the contribution of hereditary effects to total detriment is small (<3%). The ICRP (2007) detriment values are 5.7×10^{-2} Sv^{-1} for a population of all ages and $4.2 \times 10^{-}$ Sv^{-1} for a working age population (18–64 years of age at exposure). ICRP (2007) also referred to a lifetime risk of fatal cancer of about 5×10^{-2} Sv^{-1}.

ICRP has published analyses of lifetime cancer risks separately for males and females and different ages at exposure (ICRP 2021, 2022). Although the results showed substantial differences between cancer types,

Table 3. Illustration of variation in the use of terms to describe individual dose levels, depending on circumstances of exposure.

Effective dose, mSv	Cancer risk[a]	Medical patients, Emergency workers	Workers, planned	Public, planned
100–1000	10^{-2}–10^{-1}	Moderate	High	Very high
10–100	10^{-3}–10^{-2}	Low	Moderate	High
1–10	10^{-4}–10^{-3}	Very low	Low	Moderate
0.1–1	10^{-5}–10^{-4}	Minimal	Very low	Low
0.01–0.1	10^{-6}–10^{-5}	Negligible	Minimal	Very low
<0.01	$<10^{-6}$		Negligible	Minimal

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

overall risks were shown to be higher at younger ages at exposure by up to a factor of 2–3 and lower in older ages, with somewhat higher risk for females than males (by about 40%–60%).

UNSCEAR and ICRP, among others, are currently considering whether non-cancer diseases, and particularly cardiovascular diseases (CVD), should be included in low dose detriment. COMARE is also preparing a report on CVD and radiation exposures. The arguments hinge on the quality of the epidemiological data showing excess disease and the demonstration of biological plausibility, identifying mechanisms by which radiation at low doses can cause these diseases (Little *et al* 2012, 2023). There is a broad range of evidence that high doses of radiation can cause CVD and if an LNT model were to be applied to CVD, it is estimated that risks at low doses might be about doubled—that is, the risk due to CVD would be similar to the cancer risk.

4. Exposure situations

ICRP (2007) defines three exposure situations as:

- *Planned exposure situations* involve the deliberate introduction and operation of a source of radiation exposure.
- *Emergency exposure situations* may occur during the operation of a planned situation, or from a malicious act, or from any other unexpected situation, and require urgent action.
- *Existing exposure situations* that already exist when a decision on control has to be taken.

In addition, there are three categories of exposure: occupational, public and medical. In the ICRP system, dose limits apply only to planned situations of either occupational or public exposure, of 20 mSv y^{-1} and 1 mSv y^{-1}, respectively. All medical exposures are planned but are not subject to dose limits but are justified on a case-by-case basis by considerations of risks versus benefits.

In general terms, the highest doses and risks will be incurred by emergency workers as one-off exposures during the emergency response, and by patients for whom the benefit will outweigh the risk. The lowest doses and risks will apply to members of the public for whom the exposure may continue over many years and there is no direct benefit to the exposed individuals. Occupational exposures in planned situations represent an intermediate case in which doses may continue over many years but the exposed individuals gain direct benefit from employment.

Table 3 repeats the effective dose and cancer risk bands from table 2 and compares the application of descriptive terms to different circumstances of exposure. In this illustration, low doses and risks are below 100 mSv for medical patients undergoing diagnostic procedures (as in table 2) and also for emergency workers, but low dose is below 10 mSv for workers and below 1 mSv for members of the public. In both these cases, then, low dose falls below the dose limit. The protection system requires optimisation of protection below dose limits and the setting of constraints that will not normally be exceeded, as fractions of the respective dose limits. In each case, doses are in addition to those received from natural sources in the environment, which in the UK are average of about 2.3 mSv effective dose per year (PHE 2016).

The rationale for setting dose limits developed in ICRP Publication 26 (ICRP 1977) was to refer to acceptable levels of risk for fatalities generally, with values of 10^{-4} y^{-1} for workers and 10^{-5}–10^{-6} y^{-1} for members of the public, at which time the mortality risk from radiation was estimated as about 10^{-2} Sv^{-1}. In its 1990 recommendations, ICRP (1991) applied a more complex multi-attribute approach to the setting of dose limits as the boundary between 'unacceptable' and 'tolerable', including the temporal expression of risk following exposure as well as probability of attributable death. As a result, the increased estimate of overall stochastic risk by a factor of five to 5×10^{-2} Sv^{-1} was accompanied by a smaller reduction in the

occupational dose limit from 50 mSv to 20 mSv, although there was a five-fold reduction in the public dose limit from 5 mSv to 1 mSv, the reasoning being not completely clear despite lengthy analysis. The occupational dose limit was additionally recommended to apply as an average of 100 mSv over 5 years with no year exceeding 50 mSv. These dose limits were included in UK legislation (IRR 1999, 2017, IRR (Northern Ireland) 2000, 2017)); IRR (Northern Ireland) (Ionising Radiations Regulations (Northern Ireland) 2000, Ionising Radiation Regulations 2017). The 2007 recommendations did not make large changes to risk estimates and dose limits remained unchanged (ICRP 2007). The Health and Safety Executive (HSE 2001) in Britain has assessed maximum tolerable risks of fatality as 10^{-3} for workers and 10^{-4} for members of the public; the current occupational and public dose limits are in line with these values.

Many commentators, including ICRP (1977), have referred to the context of exposures to natural sources of radiation, most recently estimated as an average of about 2.3 mSv y^{-1} in the UK (PHE 2016). ICRP (1977) concluded that differences in doses received from natural background sources should not 'affect acceptable levels of man-made exposure, any more than differences in other natural risk should do'. If as intimated in early deliberations by ICRP (1977), it is deemed that an imposed risk needs to be reduced to between 10^{-5}–10^{-6} per year to be acceptable, as distinct from tolerable, by members of the public, this corresponds to effective doses of around 10–100 μSv per year, even though this is a very small variation in natural background dose.

5. Conclusions

The terms 'high' and 'low', and similar descriptors, are relative terms and may refer to different ranges depending on context. UNSCEAR (2012) and ICRP (2021) have defined levels of dose from high to low to negligible, in the contexts of the underlying scientific evidence and its application to doses and estimated risks to patients from medical diagnostic procedures. In the cases of planned exposures of workers and members of the public, different considerations apply and the level at which dose can be considered low will be successively lower. It is suggested that while a low dose may be below 100 mSv for diagnostic exposures of patients, low dose might be a reasonable description of doses below dose limits for workers and members of the public. In each case, dose is being used as a surrogate for risk—risks at low doses are uncertain and estimates may change but order of magnitude considerations are sufficient in most cases.

Data availability statement

No new data were created or analysed in this study.

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