Radiation Dosimetry for Animals and Plants

Radiation protection of the environment: providing knowledge and skills to the user community

25 November 2010

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Accompanying Notes

1. Key concepts - Dose units and quantities

Just as heat and light transfer energy, so nuclear radiation transfers energy from a source to the absorbing medium. However, nuclear radiation differs from heat and other types of radiation in that each particle or photon has a sufficiently high energy to cause ionisation - (the removal of an orbital electron from an atom). In producing ion pairs, the particles or photons of radiation lose energy to the medium, which is generally converted into heat energy.

1.1 Kerma and absorbed dose

It is often convenient to express a radiation field as the sum of the initial kinetic energies of all the charged particles transferred to a target by non-charged ionising radiation, per unit mass. The word for this quantity, or "kerma", is an acronym for "kinetic energy released in material", "kinetic energy released in matter", or sometimes "kinetic energy released per unit mass".

This quantity differs somewhat from the Absorbed dose, which is the total energy deposited in a target by ionising radiation, including secondary electrons, per unit mass. They are different when calculating dose to a volume smaller than the range of secondary electrons generated.

For low energy photons, kerma is numerically approximately the same as absorbed dose; however, for higher energy photons it starts to differ. This is because the extremely energetic electrons produced may deposit some of their energy outside the region of interest, or some may lose their energy through bremsstrahlung. This energy would be counted in kerma, but not in absorbed dose. For low x-ray energies, this is usually a negligible distinction.

1.2 Units and their significance

The ionisation of a gas provides a means of detecting radiation and the first widely used radiation unit, the roentgen, was based on the ionising effect on air of X- and γ- radiation. This unit has been superseded and the primary unit of energy transfer is the Gray (or radiation absorbed dose), where 1 Gy is equivalent to an energy deposition in any medium of 1 J kg^{-1}. 1 Gy = 6.24×10^{15} keV per kg ~ 10^{12} alpha particles per kg. Radiation energy is often measured in units of electron volts (eV), which is a typical binding energy on an electron in an atom. One electron Volt (eV) is defined as the energy gained by an electron when it is accelerated through a potential of 1 Volt. The Joule is rather a large unit for measuring radiation transformations.

Only small amounts of deposited energy from ionising radiation are required to produce biological harm - because of the means by which energy is deposited (ionisation and free radical formation). For example, drinking a cup of hot coffee transfers about 700 Joules of heat energy per kg to the body. So, transfer the same amount of energy from ionising radiation would involve a dose of 700 Gy - but doses in the order of 1 Gy are fatal.

1.3 Equivalent Dose, Effective Dose and Committed Effective Dose

The radiation absorbed dose is a very useful physical concept, but in biological systems the damage is not only dependent on the energy deposited in tissue. The density of ionisation is also important, largely because a greater density of ionisation leads to a higher probability of double strand breaks in DNA. Thus, radiation with a high linear energy transfer is liable to cause more biological damage than radiation with a lower linear energy transfer. To allow for this a quantity known as the dose equivalent is defined, which is simply the absorbed dose multiplied by a radiation weighting factor chosen to reflect the greater effectiveness of high LET radiation in causing biological damage.

The unit of equivalent dose is the Sievert (Sv) so:

$Sv = Gy \times w_R$

Where w_R is the radiation weighting factor for the radiation concerned. The value of the weighting factor is found to depend on the density of ionisation caused by the radiation, or Linear Energy Transfer (LET). An alpha particle produces about 1 million ion pairs per millimetre of track in tissue (high LET), whereas a beta particle produces around ten thousand (low LET). The quality factor (w_R) is assigned a value of 1 for gamma radiation and the values for other types of radiation are related to this in accordance with their ionisation densities. Values of w_R for the most commonly encountered radiation types are summarised below.

There is no firm consensus but only suggested values for w_r for non-human biota. These are 1 for gamma and high energy (> 10keV) beta radiation, 3 for low energy (< 10keV) beta radiation and 10 for alpha (non stochastic effects in biota) vs. 20 for humans (to cover stochastic effects of radiation).

2. Dosimetry in ERICA

2.1 Basic concepts: dose conversion coefficient and absorbed fraction

The estimation of absorbed dose rate (µGy h^{-1}) is an essential concept within the ERICA approach. Radionuclides in the environment lead to plants and animals being exposed both externally and internally to ionising radiation. Internal exposure arises from the uptake of radionuclides by the organism via pathways such as ingestion or root uptake; it is determined by the activity concentration in an organism, the size of the organism, and the type and energy of emitted radiation. External radiation exposure depends on various factors including contamination levels in the environment, the geometric relationship between the radiation source and the organism, habitat, organism size, shielding properties of the medium and the physical properties of the radionuclides present.

In the simplest case, an organism is assumed to be in an infinite homogeneous medium with the same density as itself, and have radioactivity distributed homogenously throughout its body. Under these conditions, both internal (DCC_{int}) and external (DCC_{ext}) dose conversion coefficients (defined as absorbed dose rate (µGy h^{-1}) per unit activity concentration in organism (Bq kg^{-1} fw) or medium (Bq per unit media fw)) can be defined.

For mono-energetic radiation the DCCs can be expressed as a function of the absorbed fraction:

$$DCC_{\text{int}} = E \times \phi(E)$$

$$DCC_{ext} = E \times \left(-\phi(E)\right)$$

Where E (eV) is the energy of a mono-energetic source; and ϕ(E) is the absorbed fraction for the energy E (eV). This equation is an approximation that assumes the organism and the surrounding medium are of similar density and elemental composition. If the radiation is not mono-energetic, the above definition can be generalised by summing the terms and over the different radionuclide decay energies, weighted by the branching ratios of each transition. Moreover, for external exposure, if the organism receives contributions from various environmental media, the equation also needs to be generalised by summing these individual contributions.

The key quantity for estimating internal absorbed doses is therefore the aforesaid absorbed fraction (ϕ), defined as the fraction of energy emitted by a radiation source that is absorbed by an organism.

Within the ERICA Integrated Approach, the absorbed fractions for photon and electron sources assumed to be uniformly distributed in spheres/ellipsoids immersed in infinite aquatic medium have been calculated using Monte Carlo simulation. The calculations for ERICA default geometries cover an energy range from 10 keV to 5 MeV, a mass range from 1 mg to 1000 kg, and shapes from sphere to ellipsoids with varying degrees of non-sphericity. From the computed absorbed fractions, a set of 're-scaling factors' are derived and interpolated to allow user-defined organisms to be defined within certain limitations of size.

From the calculations for mono-energetic radiation sources, nuclide-specific dose conversion coefficients (DCCs) are derived for external and internal exposure, taking into account the type of radiation as well as energy and intensity of the emission for most radionuclides included in ICRP Publication 38 (ICRP, 1983). Radioactive daughter nuclides are included in the calculation of the DCCs, if their half-lives are shorter than 10 days.

The complete description of the unique method used to derive DCC values within the ERICA is fully described in Pröhl *et al*. (2003) and Ulanovsky and Pröhl (2006) and so it will not be further described here. The tool help can also be consulted for more details.

2.2 Source - target assumptions and uncertainty estimation

For terrestrial organisms the estimation of external exposure is not simple because of the need too consider organisms living at the interface of media with different densities and finite dimensions. Source-target conventions for calculations of DCCs for external radiation within ERICA are as follows:

- External exposure of on- and above- soil organisms to a uniformly contaminated volume with a thickness of 10 cm (µGy h^{-1} per Bq kg^{-1} soil fresh weight).
- External exposure of organisms that live in the middle of a uniformly contaminated soil layer with a thickness of 50 cm (µGy h^{-1} per Bq kg^{-1} biota fresh weight).

The simplifications made when estimating whole body DCC values in the ERICA Approach are comparable with those made in other approaches to estimating exposure of non-human biota (Beresford et al 2005). The ERICA project has assessed the uncertainty associated with the heterogeneous distribution of some radionuclides and this is discussed in full in the Tool help. In summary, it can be concluded that: (i) for photons, the uncertainty due to a possible non-homogeneous radionuclide distribution is lower than 20-25 per cent in the considered cases; and (ii) for electrons, uncertainty is negligible below a threshold energy dependent on the size of the organisms.

2.3 Dose rate calculation

The dose conversion coefficients can be used to estimate the unweighted absorbed dose rate from media and organism activity concentrations. For internal exposure one can use the following equation:

$$\dot{D}^{b}_{\text{int}} = \sum_{i} C^{b}_{i} * DCC^{b}_{\text{int},i}$$

Where:

- $\dot{D}^{b}_{\text{int}}$ is the absorbed internal dose rate for reference organism *b*
- C^{b}_{i} is the average concentration of radionuclide *i* in reference organism *b* (Bq kg^{-1} fresh weight)
- $DCC^{b}_{\text{int,i}}$ is the radionuclide-specific dose conversion factor (DCC) for internal exposure defined as the ratio between the average activity concentration of radionuclide *i* in the organism *b* and the dose rate to the organism (µGy h^{-1} per Bq kg^{-1} fresh weight)

For external exposure one can use the following equation:

$$\dot{D}^{b}_{\text{ext}} = \sum_{z} v_{z} \sum_{i} C^{\text{ref}}_{zi} * DCC^{b}_{\text{ext},zi}$$

Where:

- v_z is the occupancy factor, the fraction of time that organism *b* spends at a specified location *z* in its habitat
- C_{zi}^{ref} is the average concentration of radionuclide *i* in the reference media of a given location *z* (Bq kg^{-1} fw or dw (soil or sediment) or Bq l^{-1} (water))
- $DCC^{j}_{ext,zi}$ is the dose conversion factor for external exposure defined as the ratio between the average activity concentration of radionuclide *i* in the reference media corresponding to the location *z* and the dose rate to organism *b* (µGy h^{-1} per Bq unit media).

Weighted total dose rates (in µGy h^{-1}) can be calculated as:

$$DCC_{\text{int}} = wf_{\text{low}\beta} \cdot DCC_{\text{int,low}\beta} + wf_{\beta+\gamma} \cdot DCC_{\text{int},\beta+\gamma} + wf_{\alpha} \cdot DCC_{\text{int},\alpha}$$
$$DCC_{\text{ext}} = wf_{\text{low}\beta} \cdot DCC_{\text{ext,low}\beta} + wf_{\beta+\gamma} \cdot DCC_{\text{ext},\beta+\gamma}$$

Where wf are the weighting factors for various components of radiation (low β, β + γ and α). These factors are introduced to account for the relative biological effectiveness of the

different types of radiation. Default radiation weighting factors of 10 for alpha radiation and 3 for low beta radiation are assumed within Tier 1, in line with suggested values in the FASSET project (Pröhl *et al*., 2003). This is also consistent with the upper bound on the range of variation reported by Chambers *et al.* (2006) for α-radiation weighting factors in relation to deterministic endpoints (mainly mortality). At Tiers 2 and 3, whilst these values are provided as the defaults, they can be altered by the user.

3. Special cases outside the ERICA calculation procedure

With the exception of ^{3}H and ^{14}C, ERICA does not perform assessments for gaseous radionuclides, that is, it is not designed to carry out an assessment in which the medium from which biota receive exposure is air instead of water, soil or sediment. In such cases, the user needs to resort to other tools, such as the EA R&D 128 model, or perform the calculations autonomously. When using the EA R&D 128 methodology, the following formulae are applied for radionuclides whose concentration is referenced to air: ^{3}H, ^{14}C, ^{32}P, ^{35}S, ^{41}Ar and ^{85}Kr (Copplestone et al., 2001).

$$(\text{Soil conc})_{nuclide} = (\text{Air conc, Bq m}^{-3})_{nuclide} \times CF^{\text{soil}}_{nuclide}$$

$$(\text{Air conc, Bq kg}^{-1})_{nuclide} = (\text{Air conc, Bq m}^{-3})_{nuclide} / 1.2$$

$$(\text{Internal dose})_{nuclide,organism} = (\text{Air conc})_{nuclide} \times CF^{\text{organism}}_{nuclide} \times DCC^{\text{internal}}_{nuclide,organism}$$

$$(\text{External dose})_{nuclide,organism} = (Soil\ dose + Immersion\ dose)$$

$$(Soil\ dose) = DCC^{\text{external}}_{nuclide,organism} \times \left[(\text{Soil conc})_{nuclide} \times \left(\begin{array}{l} (fsoil_{organism} + fsoilsur_{organism}/2) \\ + fair_{organism} \times (\text{reduction factor})_{\text{radiation type}} \end{array} \right) \right]$$

$$(Immersion\ dose) = DCC^{\text{external}}_{nuclide,organism} \times (\text{Air conc, Bq kg}^{-1})_{nuclide} \times (fair_{organism} + fsoilsur_{organism}/2)$$

ERICA does not have the ability to assess for noble gases such as argon and krypton. However, other tools such as the aforementioned EA R&D 128 approach have a method to modify an existing assessment to adapt for these radionuclides. This is done by assuming that the internal dose negligible: Ar and Kr CFs set to 0. No deposition is considered but some migration into soil pores is modelled by assuming pore air is at the same concentration as ground level air concentrations. A free air space of 15% is assumed, density = 1500 kg m^{-3}, so free air space = 10^{-4} m^3 kg^{-1} and Bq m^{-3}(air) x 10^{-4} = Bq kg^{-1} (wet). Hence, a transfer factor TF of 10^{-4} for air (Bq m^{-3}) to soil (Bq kg^{-1} wet) can be generated. For plants and fungi occupancy factors are set to 1.0 soil, 0.5 air (instead of 0). Biota in the subsurface soil and are taken as exposed only to ^{41}Ar and ^{85}Kr in the air pore spaces. External DCCs for fungi can be taken as those calculated for bacteria (i.e. infinite medium DCCs).

More detailed models have been developed for radon assessment in animals and plants, based in respiration allometric models, as described in Vives i Batlle *et al*. (2008), but this is wholly outside the ERICA approach.

4. References

Beresford, N.A., Balonov, M., Beaugelin-Seiller, K., Borretzen, P., Brown, J., Cheng, J., Copplestone, D., Doi, M., Gaschak, S., Golikov, S., Horyna, J., Hosseine, A., Howard, B.J., Jasserand, F., Kamboj, S., Nedveckaite, T., Olyslaegers, G., Sazykina, T., Vives i Batlle, J., Yankovich, T., Yu, C. 2005. Models and approaches available to estimate the exposure of non-human biota: An international comparison of predictions. In: The 2nd International Conference on Radioactivity in the Environment (Eds P. Strand, P. Børretzen & T. Jølle) p146-149. 2-6 October, Nice. NRPA: Østerås.

Chambers DB, Osborne RV and Garva AL (2006). Choosing an alpha radiation weighting factors for doses to non-human biota. *Journal of Environmental Radioactivity*, 87, 1-14.

Copplestone D, Bielby S, Jones SR, Patton D, Daniel P and Gize I (2001). *Impact assessment of ionising radiation on wildlife.* R&D Publication 128: Environment Agency, Bristol, UK, 2001

ICRP (1983). International Commission on Radiological Protection, *Radionuclide transformations: Energy and intensity of emissions*, ICRP Publication 38, Annals of the ICRP, Vols. 11-13.

Pröhl G, Brown J, Gomez-Ros J-M, Jones S, Woodhead D, Vives J, Taranenko V and Thørring H (2003). *Dosimetric models and data for assessing radiation exposure to biota*. Deliverable 3 to the project "FASSET" Framework for the Assessment of Environmental Impact, Contract No. FIGE-CT-2000-00102. Swedish Radiation Protection Authority.

Ulanovsky A and Prohl G (2006). A practical method for assessment of dose conversion coefficients for aquatic biota. *Radiation and Environmental Biophysics*, 45(3), 203-214.

Vives i Batlle, J., Jones, S.R. and Copplestone, D. (2008) Dosimetric Model for Biota Exposure to Inhaled Radon Daughters. Environment Agency Science Report – SC060080, 34 pp.