A System For Environmental Protection : Reference Dose Models For Fauna And Flora

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INTRODUCTION

It has previously been argued that, notwithstanding the merits of the system that has developed to ensure the radiological protection of man, there is also a need to develop criteria and frameworks that explicitly demonstrate that the environment will also be protected [1,2,3,4]. In fact, in recent years, this need has been the subject of some considerable discussion and debate, including the holding of at least two symposia [5,6] and the production of an IAEA document [7]. The continued absence of such criteria and frameworks has probably been due to several factors : the lack of a perceived need, in view of statements made by the ICRP [8,9]; the difficulty of delivering criteria and frameworks that could be applied to organisms other than man; the almost infinite range of fauna, flora, and ecosystems that exist; and the assumed sheer impracticality of incorporating any form of framework into a regulatory system. All good arguments : except, perhaps, for the first.

In order to progress the discussion, some ideas have been put forward by Pentreath [4] to develop a system for protecting the environment, based on narrowing the problem down by defining a few "reference" points. The system would consist of a set of reference dose models for a limited number of fauna and flora, reference methods to apply them to observed or calculated internal and external radionuclide distributions, plus a knowledge of the likely effects of absorbed dose on such reference fauna and flora in terms of one, two or three broadly defined biological end-points. The values obtained via this reference method approach would then be used to compare with *derived consideration levels*. These values would not be treated as standards but simply as data that would help to inform – along with other relevant environmental, economic, and societal information – the final decision making process. It would therefore be a system based on many but not all of the principles that underpin the system that has been developed for the protection of man. And it would be open, transparent, and amenable to further development via agreed sets of criteria.

BASIC ASSUMPTIONS FOR DOSIMETRY

If a system was to be built upon a set of reference, testable, methodologies then it is important to be clear from the outset what the different elements of it would and would not represent. An important consideration is the extent to which a comprehensive understanding of the effects of radiation on the environment as a whole – or indeed the effects of anything else – can be established by studying the consequences of the effects of radiation on the individual components of it. Virtually all of the known effects of radiation are mediated by damage initially occurring at the molecular level. Such damage is therefore expressed within individuals. If the damage results in early mortality, or decreases fertility or fecundity, or produces adverse mutations, then this could in turn influence the future maintenance or development of the population as a whole. But population effects would also be dependent upon the proportion of individuals exposed to different levels of radiation, and thus variously affected; the age-specific reproductive rate across the population; plus the relative effects of all of the other "pressures" and their variations to which the population is exposed. And at a community and ecosystem level, all of these factors are compounded to the extent that it would be virtually impossible to identify one adverse factor from another. In short, the most basic testable piece of information for which a dose/effect probability factor could be derived is that which applies to an individual organism.

Nevertheless, it is equally important to recognise that it would not be feasible to have a system that took into consideration every possible dose/effect relationship for any individual. It has therefore been suggested[4] that the criteria used should only be one or more of the following broad biological end points:

- early mortality;
- a reduction in reproductive success; or
- scorable cytogenetic damage.

These assumptions also place limits on the complexity of the dose models required. So what factors should be taken into account in selecting reference fauna or flora, and in deriving reference dose models for them? With regard to the former, relevant factors would presumably include:

- the extent to which an organism would be exposed to irradiation within a given environment because of its life span, life cycle and general biology;

- the chances of being able to identify effects at the level of the individual organism that could be related to radiation exposure; and
- the availability of existing relevant data or the feasibility of being able to conduct controlled experiments in order to obtain them.

And with regard to the complexity of the dose models required for such organisms, in addition to the obvious considerations of size and shape, this would clearly depend upon how one of the above three broad biological end points related to what is known about irradiation effects. It is therefore suggested that, for *early mortality*, a 'whole-body' absorbed dose model would generally be sufficient in the first instance. Similarly, for a *scorable genetic effect*, the model would need to be either 'whole-body' if the likely tissue with cells exhibiting the expression was not known, or it would have to be specific to a particular tissue or organ. But with regard to *reduced reproductive success*, this would relate to effects on both fertility and fecundity; more detailed dose models would therefore be required to estimate dose rates to gonadial tissue within the adult, and to the developing embryo. The embryo could of course be either within or external to the adult, and in the latter case the dose models would relate either to the whole, or part, of the egg and its embryo.

There is one final general basic assumption that needs to be considered, and that is how one makes allowance for differences in relative biological effectiveness (RBE). It has also been suggested by Pentreath[4] that there is a need for a specific quantity that both explicitly acknowledges the fact that RBE applies to non-human species – from which a considerable quantity of the relevant basic information was first derived – and yet also distinguishes between what is known about dose effects in man compared with other fauna and flora. In effect, a *Dose Equivalent for Flora and Fauna*, a DEFF, that would be a product of absorbed dose (D) and one or more dimensionless radiation weighting factors. It is likely that the weighting factors (W_F) would differ from one reference organism to another, as further information accrued. As a start, however, if it is assumed that

$$DEFF_F = [W_F(\beta, \gamma) \times D(\beta, \gamma)] + [W_F(\alpha) \times D(\alpha)]$$

for a specific reference organism (F), with the unit of Jkg^{-1}, then the weighting factors could be developed as follows. The $W_F(\beta,\gamma)$ would be defined as unity, and the $W_F(\alpha)$ derived as the quotient of the accepted maximum and minimum values of the linear energy transfer (LET) in water for α particles with energy up to 10MeV, and the maximum and minimum LET values for electrons with energies in the range of 0.01 to 2 MeV. Thus $W_F(\alpha)$ could be in the range 100 to 250 [10,11] but this would be substantially greater than the RBE values, in the range 15 to 70, that have been suggested for low dose rates of high LET radiations for some of the end points of interest here [12]. It is therefore suggested that a $W_F(\alpha)$ value of about 40 might be adopted for provisional application. This would at least acknowledge that the absorbed dose (Gy) is insufficient, and would differentiate the DEFF from the equivalent dose Sv, generically, until a biologically-derived set of values had been obtained. (All of this may seem a little far-fetched, in view of the relative lack of numerical changes in the rem and Sv over the years, but none of this has detracted from the theoretical approach underlying these quantities and units. The same should apply to fauna and flora.)

DOSIMETRIC MODELS

Physical descriptions of the processes by which energy is transferred from α and β particles, and from γ and X rays, have already been developed theoretically from first principles, and these have been expressed mathematically. But due to the energy-dependent and stochastic nature of the processes involved, they are not easy to apply to environmental situations. Simpler, empirical, expressions have therefore been developed, as summarized in an IAEA document [13]. These have traditionally been used to describe the distribution of absorbed dose around point sources of α and β particles, and γ rays, integrated as necessary over defined source distributions to give an estimate of dose rate at specified points in tissue, and of average dose rates within a given volume. With this in mind it is therefore necessary to consider the practicality, as well as the desirability, of their application in an environmental situation.

Before doing so, however, it is also necessary briefly to consider the possible range of geometries required. A simple hierarchy of complexity is envisaged such as:

Type A	solid sphere, ellipsoid, or cylinder to estimate whole-body dose to adult, embryo or egg;
Type B	as (A) but with an axial cylindrical cavity within, essentially to represent a gut in animals that contained a substantially different concentration of β-particle and γ-emitting nuclides;
Type C	as (A) or (B) plus one (or more) internal solid spheres, ellipsoids or cylinders to represent gonadial tissue, an internal embryo, or a specific tissue of interest because of scorable cytogenetic effects;
Type D	specific application of point source dose distribution functions for particle radiation, as for example to a specified tissue layer or layers, or because of the small size of the target; and

Type E specific multi-organ dose models, such as those that have been developed for some mammals.

And, equally important, is consideration of the possible range of 'environmental' geometries. Again, for convenience, these could be grouped into the following simple categories:

Case (a) surrounded by air (4 π);
Case (b) surrounded by water (4 π);
Case (c) surrounded by soil/sediment (4 π);
Case (d) at the interface of air and soil/sediment (2 π);
Case (e) at the interface of water and soil/sediment (2 π); and
Case (f) concentric i.e. organism surrounded by air (4 π) surrounded by soil (4 π).

Internal radiation

The geometries envisaged, with the exception of Type D, are the targets for which the dose distribution is determined by the integration of the point source dose functions, over the relevant radiation source distributions, using simple empirical expressions. With regard to internal radiation therefore, equilibrium dose rates from α-particles are relatively easily calculated for Type A, B or C geometries where dimensions are ≥ ~1mm and it is assumed that there is an energy of ≤ ~ 10 MeV and a range in tissue of ≤ ~100μm. For other cases (Type D) more detailed geometries would be necessary as, for example, to estimate dose rates arising from the adsorption of α-emitting radionuclides on the surface of a small egg [11, 14].

For β-radiations the situation is more complex, because their range in soft tissues may be up to about 2cm. Again the basic assumption where dimensions are ≥ ~2cm is that of a uniform distribution of the source. The absorbed equilibrium dose rate is then a function of the fractional number of β-particles emitted and their mean energy. Where dimensions are ≤ ~2cm then point source dose distribution functions (Type D geometry) need to be applied. The simplest approach is to divide the model (say, a sphere) into a succession of partial shells centred on the point of interest. The dose rate at that point is then simply the sum of the contributions from the sphere and the individual segments evaluated at the radionuclide concentration in the tissue using the β-particle point source dose distribution function.

The relationships between tissue dimensions, particle energy, and dose rates are particularly important in Type C geometries (and Type C geometries may also incorporate Type D). Some general examples of the relative effect of this approach, using Type C geometries, have already been produced [1]. The examples were those of 16mg and 1g ellipsoidal target organs placed centrally within 1g and 1kg ellipsoidal bodies respectively. The β-emitting radionuclide in the target organ was then assumed to be either 0.1x (discrimination) or 10x (preferential accumulation) the assumed mean whole-body concentration. At low β-particle energies – where the ranges are less than, or of the same order as, the dimensions of the target organ - the dose rate scales proportionately with the radionuclide concentration in the target organ. But at higher energies, and thus longer ranges, the dose rates fall below proportionality for preferential accumulation in the target organ, and increase above proportionality where there is discrimination.

Special consideration also has to be given to Auger electrons, and the electrons produced by internal conversion of γ-rays. These are mono-energetic. The former are generally of such low energy that their ranges in tissue are less than the smallest dimensions usually considered, but the energies and ranges of conversion electrons can be significant.

With regard to γ radiation, from assumed uniformally distributed internal sources, the smaller the organism the less the amount of energy absorbed. Again, the effects of differential accumulation – as envisaged in Type C geometries – has already been considered in a general way [1], plus the effect of overall body size.

External Radiation

Because of the small range of α-particles in either air or water, the problems of estimating dose rates from external sources are essentially the same as those for internal sources, and it has to be assumed that the radionuclide is adsorbed to the surface. But Type D geometries have been successfully used to estimate dose rates to developing embryos [11].

The situation is however somewhat different for β-particles, and substantially different for γ-rays, and depends upon the nature of the external medium. If the medium is water, then it is reasonable to assume an equivalence, more or less, between the surrounding water and the soft tissue of fauna or flora in terms of radiation absorption and scattering properties. Out of water, however, the system is more complex because of the extended ranges of the β and γ radiations, plus the substantial density variations of air, soil, and the tissues of animals and plants. In these circumstances the point source dose distribution functions are not really applicable for β-particles. And for γ-radiation the issues are even more complex, depending on the environmental geometry.

For Case (a) geometries, an UNSCEAR review [15] concluded that a simple derivation of absorbed dose

rates for γ-radiation from an estimate of air kerma has many deficiencies because it depends on assumptions of photon field uniformity, secondary electron equilibrium, and zero photon scattering. But unfortunately this remains the only method currently available. Of course for both Case (a) and Case (d) geometries (i.e. terrestrial) the situation would also be more complex when consideration is made for other sources (e.g. the irradiation of one plant by the radionuclides contained by its neighbour) and the effects of self shielding. An alternative approach therefore probably needs to be developed, perhaps using Monte Carlo methods.

Where a soil (or sediment) is involved, then obviously much depends on the spatial distribution of the γ-emitting source within the soil or sediment. It then either has to be assumed that they are distributed to a depth greater than the mean free path of absorption (i.e. > ~ 1m) or they are not. Rather interesting but quite complicated environmental geometries are those envisaged in Case (f), where a terrestrial organism inhabits a burrow, and is thus surrounded by air, and beyond that, by soil.

Finally, there is one further factor that needs to be carefully considered: the relationship between the physical half-life of the radionuclide and the period over which the calculation of exposure has any biological relevance. For this reason, dose-rates to fauna and flora are often given with temporal units of hours or days, rather than per annum. And where the concentration of a long-lived radionuclide is low and, say, the development period of an embryo is short, then the resultant dose rates can only be interpreted in terms of a probability function, as has been done for developing fish eggs [16].

REFERENCE DOSE APPLICATION FACTORS

Dosimetric models can of course be applied directly to observed environmental concentrations of radionuclides. But one of the purposes of going to the effort of deriving a system to protect the environment is that of applying it to all possible situations. The dose models therefore need to be easily related to radionuclide concentration fields generated by environmental distribution models, and in a standard way. Indeed, one of the great advantages of the system that has been developed for human radiological protection is the ability to estimate dose rates to a reference man, woman, or child using tabulated dose per unit intake values. These values relate to standardised physiological models. It would therefore be useful to relate reference fauna and flora dose models to environmental ones, in a similar manner, by way of agreed sets of tabulated data that could be updated in an orderly way as new information arose. An attempt was made to do this for a number of examples in the marine environment [1] by relating the concentration of the radionuclide in the organism to that of the water by way of a concentration factor; to the concentration of the radionuclide in the sediment by way of a k_d value; and then summating the dose rates from both internal and external sources. A similar approach has since been made for certain terrestrial and freshwater organisms[17, 18].

SELECTION OF REFERENCE FAUNA AND FLORA

This is probably the most difficult aspect of all, but before considering in detail the selection of fauna and flora that could be used in a reference context, it is worth examining what the system outlined by Pentreath [4] actually intended to achieve. Essentially it was to:

- admit that we cannot provide a general assessment of the effects of radiation on the environment as a whole <u>but</u>
- by using a reference (Peer reviewed) set of dosimetric models, and
- a reference set of environmental geometries
- applied to one or more reference sets of fauna and flora likely to occur in that environment then, when applied to
- a given actual (or calculated) distribution of radionuclides in the environment,
- one should be able to make some sort of statement about the probability and severity of the likely effects of that level of radiation on such individuals, in terms of early mortality, reduced reproductive success, or scorable cytogenetic effect, by reference to data sets on what is known about the effects of radiation on the same or similar types of organisms.

A fuller environmental assessment could then be made by considering the extent of the “population” of such individuals likely to be exposed to the risk of such effects, plus all of the non-radiologically derived biological and any other information that might be relevant. Comparisons could also be made with dose rates received from background radiation, using the same “reference” methodologies and data sets. None of this would in any way prejudice the use to which the outcomes of such calculations would be put, in a managerial context. Nor would it pre-judge whether or not the results and their predicted consequences “mattered”; that would be for others to judge. But at least the derivation of the information, and the conclusions drawn from them, would be amenable to open examination.

So where does this lead in terms of the selection of reference fauna and flora? It would be quite impractical to consider very specific examples (in other words, a particular species, or even genus) but, equally,

it would be of little value to generalize to the level of stating that the reference was no more than, for example, a 'flat' fish. All of which would indicate that a generalization down to family level would be needed, where possible. There is also a limit to which the geographic range of particular reference organisms could be applied.

Nevertheless, it is sensible to begin with the models and data that we already have, in terms of methodologies and data on doses and effects. The most generally applicable are those that relate to the aquatic environment. Thus some simple Type A models have already been developed for "phytoplankton", small planktonic crustacea, large benthic crustacea, benthic molluscs, pelagic and benthic fish, a seabird and its eggs, a seal and a whale [1,19-25], although further consideration would have to be given with regard to what exactly (e.g. at family level) a number of these geometries could more specifically be taken to represent. In some cases, however, the models have been developed for a particular species, so one would then have to consider the extent to which one could generalize.

Type B models have yet to be used but Type C models have been developed for specific purposes [22,26]. The Type D models have been used to calculate dose rates to developing fish embryos [11], and more detailed Type E models have been developed for laboratory studies of the effects of internal sources in mammals (e.g. Momeni et al [28]). Further work is also necessary to consider the different Classes of environmental geometries, especially with respect to the terrestrial environment. But it is not the intention to review or list here the total amount of work that has already been done. The subject as a whole has been reviewed many times, most recently by UNSCEAR [15].

DISCUSSION

It seems both necessary and feasible to develop a discrete system for the protection of the environment from ionizing radiation, and to do so in a structured way. A key feature of such a system would be to develop a limited set of reference organisms, with their relevant reference dose models and data sets. Indeed much information already exists, but this has not been examined by way of a structured, framework approach. If such an approach is taken, however, then it helps both to organise logically what is known, and identify future research needs. At present we cannot even compile basic data sets, in a structured way, to describe the background dose rates received by fauna and flora in the world around us. And this is the situation more than a century after radiation and its effects on living tissue were first discovered. Even worse, we cannot adequately account for the potential effects of radiation on the environment – however minimal this may be for controlled releases – under all potential circumstances, and all uses, of nuclear energy and the disposal of its wastes. The development of sound dosimetry is the cornerstone of any attempt to redress this situation, and the brief analysis discussed in this paper will be used as a basis for further research.

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