REVIEW OF CURRENT METHODS IN INTERNAL DOSIMETRY OF NON-HUMAN BIOTA

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This paper consists of a discussion of the existing models utilized in the internal dosimetry of non-human biota as well as the relevance and potential use of such models in terms of waste management. Additionally, it provides example development, application, and comparison of these models with existing data for rainbow trout. The models generally provide similar results, but each has certain benefits. Benefits of ellipsoidal and stylized models include simplicity to develop and apply, where the benefit of voxel and hybrid models is high fidelity for the particular organism of concern. Additionally, anthropomorphic computational models utilizing specific organs have the ability to calculate cross-fire (dose between organs). Although voxel models are the most realistic of the models discussed, they have the drawback of significant resource dedication to develop for similar results. Additionally, the ellipsoidal and stylized models can be easily scaled to represent different organism sizes, whereas a voxel model cannot be. Refined dosimetric models may prove useful in demonstrating regulatory compliance in post-closure assessment, especially in cases where initial screening criteria are exceeded.

I. Introduction

Over the past decade or so, public interest in nuclear energy, decommissioning, and waste management and stewardship has increased, leading to a renewed interest in radioecology, or the study of the relationships between ionizing radiation and the environment. Several groups supporting collaborative radioecological research have recently been established, including the European Radioecology ALLIANCE in 2009, the Strategy for Allied Radioecology (STAR) network in 2011, and the National Center for Radioecology (NCoRE) in the United States in 2011. Although the original and primary aims of the International Commission on Radiological Protection (ICRP) radiation protection recommendations have focused on ensuring adequate protection of human beings from exposure to radiation and radioactive material, the protection framework has recently been extended to include protecting the environment from harmful effects of radiation as well.[1] Radionuclide migration from a waste disposal facility may pose a risk to non-human species, either directly or through habitat alteration. However, dose-effect data for non-human species is limited, especially at lower radiation doses and dose rates. This is generally due to a lack of appropriate dosimetry, which makes assessment of impacts to non-human biota challenging.

Several radiation modeling software programs exist, based on the idea that data for certain reference organisms (termed "Reference Animals and Plants" by the ICRP[1]) can be applied to similar species for radiation dose determination. For example, two common programs are RESRAD-BIOTA[2] (4 reference organisms) and the ERICA tool[3] (about 40 reference organisms). Various inter-comparisons of these and other modeling approaches have been conducted, with transfer factors typically being the biggest contributor to variation between models.[4-6] Additional study is being conducted in this area, including the development and continued improvement of an open source Wildlife Transfer Database.[7] There is some variation between models in dose determination, but beyond that, there is discussion as to whether the existing ellipsoidal phantoms are the "best" choice for modelling potential radiation dose in the reference organisms.

Available dosimetric models have improved over the last five years, and this paper compares the existing models for internal dosimetry of non-human biota, namely, the ellipsoidal models currently recommended by the ICRP, stylized models consisting of geometric organs of relevant size and shape, and voxel models, which are three-dimensional representations of actual organisms, with brief discussion of the most recent hybrid phantoms employed in pre-clinical dosimetry.

I.A. Current dosimetric methodology

Radiation dose rates to biota are typically approximated utilizing dose conversion factors (DCF), which are values for absorbed dose rate per unit activity concentration in the body or organ (mGy d^{-1} per Bq g^{-1}). The current methodology employed by both the ICRP and the ERICA Integrated Approach[8] for calculating dose conversion coefficients employs Monte Carlo modeling of a uniformly distributed radionuclide within an ellipsoidal

phantom designed to represent hypothetical organisms.[1,9] It has been shown that when computing whole-body DCF, the assumption of a homogenous distribution will result in an uncertainty of less than 30% for both electrons and photons when comparing to a monoenergetic point source at the center or periphery of the ellipsoid (which gives the range of possible DCFs).[9] However, if a radionuclide is not homogeneously distributed but instead concentrates in a particular organ (e.g. iodine-131 in the thyroid) a much higher dose will be received by the organ or tissue than by the whole body. Organs have been generically modeled as spheres within the whole-body ellipsoid phantom[1] to address situations where nuclides concentrate in an organ, but this simplicity may be insufficient to accurately represent the complex and variable nature of organ structure and arrangement within different types of organisms. The ratio of whole-body to organ mass offers a conservative conversion of whole-body to organ dose, but may be a considerable overestimate.[9]

Establishment of appropriate screening levels in the regulatory paradigm requires incorporation of sufficient knowledge of dose effects; the ICRP currently lists no derived consideration reference levels for organs, meaning that specific risks associated with organ dose rates are unavailable.[1] Note that while implementing organ-specific screening levels from a regulatory standpoint may be impractical, giving consideration only to whole body absorbed doses or dose rates may not be adequately protective against detrimental effects of ionizing radiation. Relating effects to dose requires either a direct determination of dose or a modelling methodology for dose approximation. Direct dosimetry is possible in certain situations (for example, GPS-dosimeter collars), although not often feasible. In the absence of such dosimetry, robust dosimetric models are needed to approximate the radiation doses received by the environment. Accuracy is important in dose-effects studies; relating an effect to an underestimate of dose (or dose rate) may result in unnecessary and expensive remediation efforts. Conversely, if the dose (or dose rate) required to cause an effect is overestimated, regulatory bodies may establish environmental protection standards at levels not adequately protective.[10] Lack of appropriate models results in occasional controversy surrounding studies related to the effects of radiation on the environment,[11] which emphasizes the need for development, refinement, and harmonization of dosimetric modelling approaches.

The need for refined, consistent dosimetric methodology is particularly relevant in waste management, as regulations in several countries require specific consideration and assessment of post-disposal radiological impacts on the environment. Two prime examples are Sweden and Finland, as each currently has a repository license application under regulatory review.[12]

Since the ICRP's recommendations in 2008, radiation protection in the environmental setting has focused on maintaining biodiversity and limiting adverse population effects; i.e., dose limits are established to protect against such endpoints as population decline. This focus on population and ecosystem impact is maintained in the aforementioned regulatory requirements. The Finnish regulations[13] specify that an impact assessment should demonstrate that there will be no significant population-based detriment, whereas Swedish regulatory guidance[14] advises inclusion of organisms in the impact analysis based on ecosystem importance as well as "their protection value according to other biological, economic, or conservation criteria."

Although the various models discussed here involve dose determination for an individual organism, there is relevancy to this methodology beyond the protection of the individual. Dose levels at which effects are seen across individuals can lead to an effect on the population (although there is debate concerning the suitability of reference organisms for this purpose.)[15] For example, a decline in reproductive success or absence of sexual development in individual trout, such as resulting from a significant ^{131}I exposure,[16] could lead to a decline in trout population. Improved dosimetric methods will enable the ability to relate exposure to dose and dose to effects, ultimately determining the risk associated with exposure to radiation. Model comparison and refinement is important to the process of determining dose rates, doses, and dose effects.

I.B. Computational models

Computational phantoms have found extensive use through incorporation into Monte Carlo based radiation transport computer codes for application in radiation dosimetry, as well as in medical imaging simulation and evaluation.[17-18] Through the early 2000s there were considered to be two main classes of anthropomorphic computational models.[17] The first, stylized phantoms, were developed in the 1960s and use combinations of simple, equation-based surfaces such as cylinders and spheres for object representation. The second, voxel phantoms, were originally created in the 1980s following the advent of more powerful computing technologies and imaging techniques. Objects in a voxel phantom are represented by three dimensional voxel matrices. A third class of computational phantom emerged in the 2000s as a hybrid of stylized and voxel phantoms.[18] These hybrid phantoms utilize non-uniform rational B-spline surfaces (NURBS) (commonly used in 3D computer graphics) and can even be used to simulate movement as so-called 4D phantoms.[19] The translation of this type of phantom for use within radiation transport codes is non-trivial,[18] and involves conversion back to a voxel model prior to implementing the radiation transport model.[20] However,

hybrid models allow flexible manipulation of organs and the body, allowing one or more selected organs to be refined as desired.[21] A significant amount of research has been conducted concerning human model development, however work conducted in creating animal models beyond mice and rats is lacking.[17] The initial research and subsequent increase in animal model development over the past decade was motivated by the need for refined preclinical models, and therefore initially focused on laboratory animals.[17] There is currently even an online program that utilizes a suite of hybrid computational phantoms for murine dosimetry.[21] In recent years, however, there has been increased emphasis on radiation protection of the environment, and some models have been used for this specific end.[10,23-28]

Table 1 contains selected studies[10,19-21,23-37] (apart from ERICA and other modeling software) that have developed computational phantoms for non-human biota, with indication of phantom type and whether or not dosimetric information was provided.

TABLE 1: Selected studies that have developed computational phantoms for non-human biota

Biota	Study	Phantom type	Dosimetric data
Mouse	Segars et al. 2004	Hybrid	No
	Hindorf et al. 2004	Stylized	Yes
	Stabin et al. 2006	Voxel	Yes
	Dogdas et al. 2007	Hybrid	No
	Taschereau et al. 2006	Hybrid	Yes
	Bitar et al. 2007	Voxel	Yes
	Mauxion et al. 2013	Hybrid	Yes
Rat	Stabin et al. 2006	Voxel	Yes
	Xie et al. 2010	Stylized, voxel, hybrid	Yes
	Zhang et al. 2009	Hybrid	Yes
Trout	Ruedig et al. 2014	Voxel	Yes
	Martinez et al. 2014a,b	Stylized, voxel	Yes
Frog	Kinase 2008	Voxel	Yes
Crab	Caffery and Higley 2013	Voxel	Yes
Canine	Padilla et al. 2008	Voxel, hybrid	Yes
	Kramer et al. 2012	Voxel, hybrid	No
Arabidopsis thaliana	Biermans et al. 2014	Stylized	Yes

A few of these studies have compared the variation between different phantom types with generally consistent results for whole body, but varying results for organ doses.[20,21,28,35] The variation between organ doses in stylized vs voxel/hybrid models is attributed to variation in organ shape, location, and orientation. Simple ellipsoidal models (as in the ERICA tool and as endorsed by the ICRP), on the other hand, assume spherical organs only, and organ dose (or similarly dose rate) is related to the corresponding whole body values by equation (1) (Ref. 9).

$$D_{\text{organ}} = D_{\text{whole body}} \left(\frac{\text{AF}_{\text{organ}}}{\text{AF}_{\text{whole body}}} \right) \left(\frac{m_{\text{whole body}}}{m_{\text{organ}}} \right) \quad (1)$$

where AF is the absorbed fraction, or the proportion of energy emitted and absorbed in the organ or whole body as specified. In the absence of organ-specific AF data, a conservative estimate of organ dose is determined by (2):

$$D_{\text{organ}} = D_{\text{whole body}} \left(\frac{m_{\text{whole body}}}{m_{\text{organ}}} \right) \quad (2)$$

The mass ratio approach discussed here is only valid for source organs; that is, the assumption when applying equation (2) is that the source resulting in $D_{\text{whole body}}$ is contained within the organ for which D_{organ} is being calculated. This approximation becomes more accurate as organism size increases because the absorbed fraction quotient between organ and whole body increases accordingly; larger organs will self-absorb more radiation than smaller organs, especially for low penetrating radiation (e.g. beta radiation).[28]

II. MODEL DEVELOPMENT

Organs are represented by simple geometric shapes in stylized phantoms. Ideally these shapes are chosen and located within the body of the organism to be as anatomically relevant as possible. This can be accomplished through expert knowledge of the organism of interest, or through dissection or imaging.

There are four general steps in the procedure for creating a voxel phantom.[17-18] These include: (1) acquiring an appropriate full-body image set; (2) identifying and segmenting organs or other anatomical structures of interest within the image set; (3) determining density and elemental composition characteristics for the identified tissues; and (4) converting the organ segments (contours) to a 3D volume for visualization (verification of appropriate organ structure) and Monte Carlo implementation. Image sets (step (1) above) are typically acquired from CT, microCT, MRI, or cryosection photography. Images are then imported into contouring software such as 3D-Doctor (AbleSoft) where organs are manually outlined. Human tissue composition has been used for biota tissue composition across the animal studies; there is definite need to investigate the effect tissue composition has on dose determination for truly representative dosimetry. The organ contour lines are consolidated into a 3D rendering of the two-dimensional segments for visual confirmation of the structure. This set of organ contours is then converted into a single boundary file and transformed into an appropriate lattice structure for radiation transport simulation. Voxelization (converting solid geometry to voxels) is achieved by

multiplying the pixel size (determined by image resolution) by the thickness of an image slice, converting the 2D pixels into 3D voxels.[15] This conversion is often completed using an in-house MATLAB based program,[20,35] although HML Canada offers their Voxelizer software to interested parties at no charge.[38] Finally, the radiation transport code is implemented. Typical Monte Carlo codes used for this purpose are MCNP/MCNPX (the most common), EGS4, GATE, and GEANT 4.[21]

Hybrid, or NUBRS, model development is similar to voxel construction, only with additional steps. After organ models are segmented, they are imported into an appropriate computer code (such as Rhinoceros; McNeel North America) and 3D NURB surfaces are fit to each segmented structure to generate a mathematically defined model. Organs may be scaled, smoothed, or otherwise refined during this step. As individual organs are adjusted during this stage, the final whole body model must be analyzed and adjusted to ensure no organs overlap. Finally, voxelization requires "re-meshing" of the NURBS model, or converting back into a boundary file. This boundary file is then converted into an appropriate voxel model, as above.[20,36]

The following example of the creation and comparison of stylized and voxel models is provided based on previous work.[27,28] Figure 1 pictures the original organism and the models developed for it.

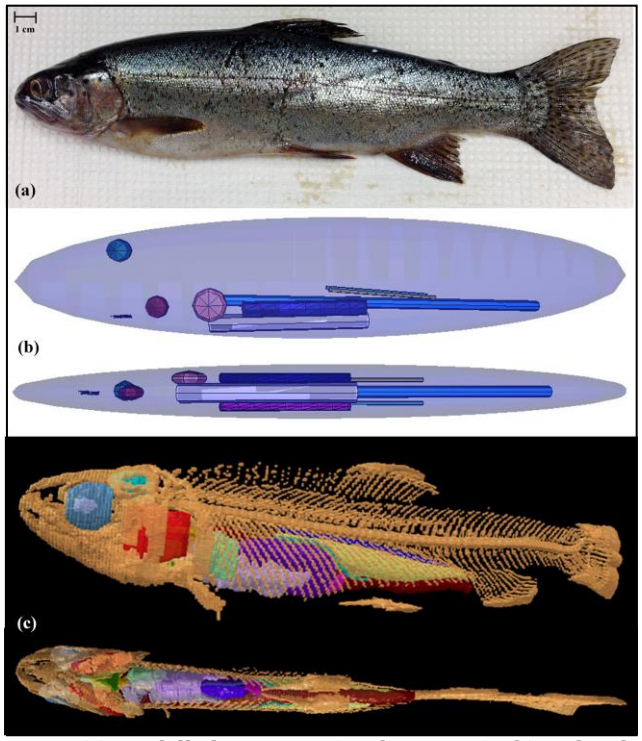

Fig. 1. (a) Modelled organism (rainbow trout); (b) stylized model (side and bottom view); (c) voxel model (side and bottom view)

Figure 1(a) is the modelled organism, a female rainbow trout. Figure 1(b) is the stylized model created based on dissection and analysis of CT slices, and Figure 1(c) is the voxel model representation of the trout (referred to as CSUTROUT), created as described above. Additionally, the studies that developed these models also considered temporal changes in ^{131}I and ^{99}Mo activity concentration data in the organs of rainbow trout.

Figures 2 and 3 show the general results of the model comparisons for ^{131}I uptake and ^{99}Mo uptake respectively. Results are shown for the maximum dose rates attained as a result of these uptakes. Both figures are presented with a log-scale ordinate. For ^{131}I uptake (Figure 2), source organs (that is, organs accumulating iodine) were the thyroid, liver, and GI tract while for ^{99}Mo uptake (Figure 3), source organs were only the liver and GI tract.

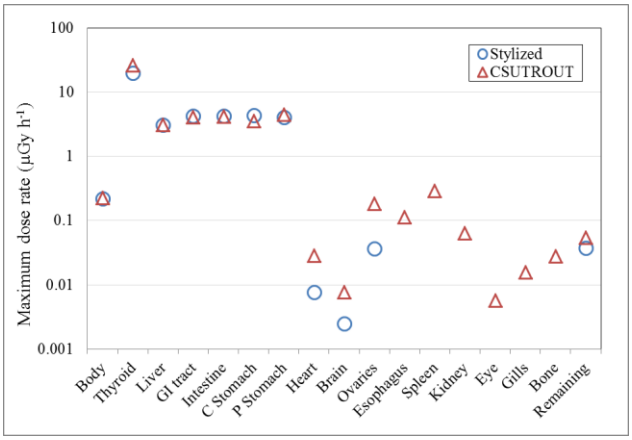

Fig. 2 Comparison of maximum absorbed radiation dose rates received from uptake of ^{131}I resulting from a single release of ^{131}I, as determined by a stylized and voxel model.

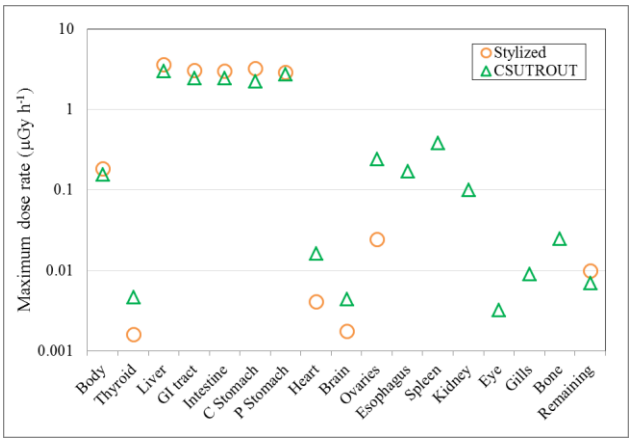

Fig. 3 Comparison of maximum absorbed radiation dose rates received from uptake of ^{99}Mo (including contribution from the daughter ^{99m}Tc) resulting from a single release of ^{99}Mo as determined by a stylized and voxel model.

Figures 2 and 3 resulted from single releases (in separate instances) of short half-life radionuclides. The radionuclides released served as tracers for analysis of mineral metabolism and lake productivity, and were not part of a dose-effect study.[39] For perspective, the default screening level utilized by the ERICA tool and recommended by the PROTECT project for environmental impact assessments is 10 μGy h^{-1} (Ref. 40). Models were generally very close in prediction of radiation dose and dose rates, especially for source organs. The stylized phantom had a tendency to provide slightly lower results, consistent with previous work.[35]

III. DISCUSSION

Although the voxel and hybrid phantoms provide the most anatomically relevant models, the development process is very time-consuming, especially for the hybrid models. Automatic segmentation is an available feature of 3D-Doctor, but cannot adequately distinguish the various soft tissue organs. Manual contouring of organs on the original image set is labor-intensive, tedious, and involves user-specific assumptions about anatomy. Additionally, several organs have very low image contrast, making the segmentation nearly impossible, and other organs can be so small as to be beyond the resolution of the CT image slices. For organ dose calculations numerous internal organs/tissues have to be identified and contoured, and the resulting size of a whole-body computational phantom with organs can potentially be too large for Monte Carlo codes to process.[18] The number of voxels the boundary file (organ contours) is composed of can be changed, but resolution is sacrificed. Whereas stylized phantoms can be easily scaled to different sizes,[27-28] the voxel phantom developed is specific to the individual organism modelled. Different species, sizes, life stages, and sex will require a different voxel phantom be developed for the most realistic dose assessment. These issues are consistent with voxel phantom development in general.[18] Hybrid models can also be rescaled and even used to represent movement, yet require even more resource dedication than voxel model development and must be converted back into boundary files prior to dosimetric analysis. It remains to be seen if hybrid models provide significant or worthwhile improvement over voxel based models.

For organisms with morphology similar to an ellipsoid, as the rainbow trout shown here, the simple models provide nearly identical whole body values to the voxel phantom. Some morphologies, such as the roots of plants, may be more difficult to represent with ellipsoids. In these cases, larger differences would be seen between simple, stylized, and voxel models.

For all models, the extent to which tissue and gut content elemental composition will impact the results reported here is currently unknown, and warrants further investigation (currently in progress). For small biota, a high resolution image set (such as obtained by microCT) used to create the voxel phantom will improve anatomical accuracy, although as the stylized phantom and CSUTROUT provided similar results, the added benefit of such increased detail is not clear.

Figure 2 demostrates a situation where the dose rate to a particular organ was two orders of magnitude greater than that of the body, implying that there may be instances where consideration of only whole body absorbed dose rates may not be sufficiently protective, especially if the organ in question is known to be radiosensitive.

Using the mass ratio approach (considering source organs individually) has been shown to be a reasonable approximation for calculating organ dose.[8,28] However, the mass ratio approach is only valid for organs with preferential uptake of a radionuclide, and cannot account for contributions from multiple source organs. Therefore, one significant benefit of more detailed phantoms (stylized, voxel, hybrid) is the ability to consider multiple source organs when determining radiation dose, along with the ability to determine dose in organs due to "cross fire," i.e. the ability to calculate dose to organs from other organs.[10,28] Note that it is possible to model individual organs as ellipsoids within the ERICA tool, although this would also not account for potential cross fire between organs.

All aspects of a site environmental impact assessment, from data collection to various model implementations, are associated with some amount of uncertainty with initial screenings generally built upon a number of assumptions, simplifications, and conservativisms.[41-42] While refining dosimetric methods will contribute to the uncertainty reduction, the benefit gained may be lost in the uncertainty of other aspects of the assessment. Consideration should be given to other aspects of the assessment when balancing the cost and effort associated with model improvement.

IV. SUMMARY AND CONCLUSIONS

Although the improved dosimetric models discussed herein provide higher fidelity and flexibility than the traditional homogenous ellipsoids, some limitations remain. There may be instances where a detailed phantom such as CSUTROUT is appropriate, as it will provide the most sophisticated radiation dose and dose rate information for the size, sex, and species considered, but generally, the stylized phantom appears to be the best choice for an ideal balance between detail and resource requirements.

Analyzing the various dosimetric models work towards eventual application and integration into the regulatory paradigm of environmental protection of non-human biota. For example, any relatively detailed model

could be used in demonstrating regulatory compliance in environmental protection. Typically, doses and dose rates from geological disposal facilities are very low; however, there have been instances where initial screening exercises result in dose rates that exceed the 10 μGy h^{-1} screening value.[42] In this instance, where a more detailed assessment is required, it may be helpful to consider a more anatomically realistic dosimetric model. Additionally, although there has not been studied consideration of this issue, detailed models such as the voxel and hybrid phantoms may also be useful when involving stakeholders; a model that looks like the organism is intuitively "more correct" than a generic ellipsoid.

Although a number of studies have been conducted investigating appropriate screening criteria for regulatory implementation, these criteria are not consistent between countries and no specific approach exists for performing a detailed post-closure assessment should a criteria be exceeded.[43] Recent consideration has been given to this issue, resulting in an internationally developed, multi-part assessment framework intended to provide a proportionate, risk-based approach to post-closure assessment.[43] A portion of this framework includes undertaking progressively more refined assessments and improved models. The dosimetric models discussed here could serve as such progressively improved models, especially if models were developed for particular organism(s) of concern.

Beyond waste management, experiments conducted to determine specific radiation effects can be supplemented with the models developed here to equate effects with certain doses or dose rates. Relating radiation dose to the effects of radiological contaminants in organisms and ecosystems has applications in emergency response and recovery as well as resource management. Knowledge of the impact of an accidental (or purposeful) release of radiation has specific and beneficial utility for general assessment and protection of environment health.

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