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Report on Methods for Wildlife Dosimetry

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Executive Summary

This milestone report concerns wildlife dosimetry and reviews how radiation transport codes and computational phantoms can be used in this field, in conjunction with information on the biodistribution of radionuclides in wildlife. The report is an input to subtask 3.3.1 of Work Package 3 (WP3) within the Strategy for Allied Radioecology (STAR) Network of Excellence [1]. The primary focus is on computational dosimetry and therefore the crucial role of accurate and standards-traceable experimental dosimetry is not discussed. The term computational dosimetry is mainly taken to refer to Monte Carlo based methods employed on mathematical, voxel or BREP phantoms. Other computational methods are not discussed.

The report features a brief introduction to state-of-the-art, generic Monte Carlo radiation transport codes and to computational phantoms. It is emphasized that generalized radiation transport codes which are applicable to humans, such as EGSnrc [2], the MCNP-family [3] or Geant4 [4-6], are equally appropriate for wildlife. The limiting factors of Monte Carlo codes are summarized to comprise the types and energies of particles that can be accurately tracked, the physical interactions, materials and geometries that can be handled, the speed of the simulations and the ease of implementation for the user.

Special emphasis is placed on the concepts of accuracy and precision in wildlife dosimetry, by juxtaposing the arguably great precision of computational phantoms against the overall relatively low accuracy of dose assessments, when features such as spatially and temporally heterogeneous activity distributions and life stages are taken into account. The resulting relatively moderate requirements on computational dosimetry in environmental management and assessments are contrasted with the much more sophisticated methodology required in research. This gradient in requirements is matched by an opposing trend in the number of individuals that are considered, in that on the one hand environmental management concerns whole ecosystems, while research may concern only a relatively small set of individuals of a single species. Whereas it is clear that computational wildlife dosimetry has a strong role to play in the latter category, it is on the contrary unclear whether sophisticated computational dosimetry has a role to play in environmental management.

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1. Wildlife dosimetry in STAR

This milestone report concerns wildlife dosimetry and reviews how radiation transport codes and computational phantoms can be used in this field, in conjunction with information on the biodistribution of radionuclides in wildlife. The report is an input to subtask 3.3.1 of Work Package 3 (WP3) within the Strategy for Allied Radioecology (STAR) Network of Excellence [1]. More specifically;

> *Subtask 3.3.1 will conduct a critical review of radiation transport codes and their application to wildlife dosimetry as well as of the current knowledge about the distribution of radionuclides within nonhuman organisms.*

The overarching aim of WP3 is to address the need for an integrated approach to human and nonhuman radiation protection. Such an integrated approach is in line with the 2007 recommendations of the ICRP [7], which state that in the context of environmental protection;

> *The Commission's aim is now that of preventing or reducing the frequency of deleterious radiation effects to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities and ecosystems.*

The current report serves to address how computational wildlife dosimetry can contribute towards this aim. The crucial role of sufficiently accurate dosimetry in dose-effect studies is particularly emphasized. A short introduction to state-of-the-art, generic Monte Carlo radiation transport codes and to computational phantoms is provided to underline their broad applicability as well as their limitations. The basic principles underlying Monte Carlo radiation transport codes are reviewed briefly, as are the basic steps needed for creation of a computational phantom. Current knowledge on the biodistribution of radionuclides is revised with emphasis on areas where new knowledge is needed. This is particularly true in situations where spatially or temporally heterogeneous activity concentrations are determining for the delivered doses. The final chapter concerns requirements of accuracy and precision in wildlife dosimetry, taking into account whether the overarching aims of an assessment are regulatory or research oriented in scope.

1.1 The current framework for radiation protection of the environment

Over the last two decades, several collaborative projects on radiation protection for wildlife have been funded by the European Commission (EC, see Table 1). The PROTECT coordinated action [8] has recently summarized that a system of radiation protection for wildlife requires methods to [9]:

- *estimate transfer of radioactivity to wildlife;*
- *calculate dose rates to wildlife;*
- *characterise risk.*

From a regulatory perspective, these points are currently addressed by a wildlife transfer parameter database [10, 11], the FREDERICA radiation effects database [12, 13] and the ERICA Tool [14, 15] for tiered risk assessments, along with other similar or complimentary tools [9].

1.2 Wildlife dosimetry in ERICA Tool and the use of simple models

The ERICA Tool uses concentration ratios (CRs) to estimate whole-body activity concentrations in biota ($Bq \cdot kg^{-1}$) from activity concentrations in soil, air or water (respectively in $Bq \cdot kg^{-1}$, $Bq \cdot m^{-3}$ or $Bq \cdot l^{-1}$) [15]. Weighted total absorbed dose rates (in $\mu Gy \cdot h^{-1}$) are obtained from external and internal whole-body activity concentrations through the application of dose conversion coefficients (DCCs) and by the use of radiation weighting factors [15]. The dose conversion coefficients are derived from Monte Carlo radiation transport simulations performed on simple spherical or ellipsoidal models of uniform composition and density [16-18]. Built-in algorithms in ERICA Tool are available for extrapolating the precalculated DCCs from Monte Carlo simulations to DCCs for user defined ellipsoids or masses depending upon whether exposure scenarios pertain to aquatic or terrestrial ecosystems [19]. Based on the resulting whole-body absorbed dose rate estimates and a risk quotient based on their magnitude relative to a screening dose rate, the more advanced Tiers 2 and 3 of ERICA Tool respectively use a lookup table or interface with the FREDERICA effects database to report on biological endpoints such as morbidity, mortality, reproductive capacity and mutation [15]. Note in particular that these are individual-level endpoints and that effects on the population level may not be trivially apparent from these endpoints [20].

The uncertainties associated with the use of simple shapes for DCC calculations in ERICA Tool are generally small compared with the uncertainties introduced by methods employed for other input parameters, such as e.g. the use of extrapolation techniques to fill in missing concentration ratios [21]. An improved understanding of transfer is therefore a focus agenda in STAR [1] and in COMET [22]. More realistic dosimetric models for a set of selected reference organisms in ERICA Tool could nevertheless be useful for rigorously quantifying the inaccuracies associated with the use of simple shapes and whole-body rather than organ doses [17, 23], although in a regulatory context the use of simple shapes for estimation of DCCs is likely fit for purpose.

In particular, it has been demonstrated that simple shapes provide good approximations of dose rates in external exposure scenarios. The relative errors on whole-body dose rate estimates that result from assuming homogeneous rather than organ-specific activity distributions in ellipsoidal models have moreover been found to generally fall below 30% [23]. Keeping in mind the overall accuracy of assessment tools such as the ERICA Tool, it is therefore reasonable to conclude that any excess precision introduced by the routine use of more advanced computational phantoms in generalized environmental management systems is not currently warranted. It is however important to note that for calculations of self-absorbed fractions or organ-to-organ crossfire, simple shapes are not appropriate [23] and more realistic computational phantoms are in such cases necessary for accurate dosimetry.

1.3 Wildlife dosimetry in dose-effect studies and the use of more realistic models

Because only modest accuracy may be gained in applying more realistic dosimetric models within existing wildlife impact assessment approaches, reflecting the fact that uncertainties in the assessments lie elsewhere [24], the strongest impact of improved dosimetric models for wildlife is likely to occur in dose-effect studies, where sufficiently accurate dosimetry is paramount [25] and exposure conditions furthermore are well characterized (or should be). In particular, because new data on biological effects currently are accumulated from studies on wildlife or laboratory animals, improvements to dose-effect studies could also to a degree benefit human assessments [26], at least from the point of view of mechanistic effects. A recent NIST journal publication [25] emphasizes that experiments which seek to determine

the biological effects of radiation exposure must be grounded on sufficiently accurate and precise dosimetry. Such studies should include considerations of the following parameters and their associated uncertainties [25]:

- *Radiation field(s) to be used (e.g., radiation output, uniformity, energy)*
- *Absorbed dose throughout the biological subject*
- *Dose uniformity within the subject*
- *Reproducibility of dose across a study group*

For controlled laboratory studies, sufficiently accurate dosimetric models of exposed individuals are a prerequisite for meeting the middle two requirements.

1.4 Transfer and biodistribution of radionuclides for internal dosimetry

Considerations on the topics of transfer, bioaccumulation and biodistribution of radionuclides should typically precede computational dosimetry (e.g. Monte Carlo simulations) in dose assessments for wildlife. Because of the inherent complexity of the issue and the large number and variability of parameters which may affect uptake and distribution, these topics are typically also determining for the accuracy of wildlife dose assessments and are as such currently receiving strong focus in the research community [11, 22]. In particular, in contrast with computational dosimetry that basically deals with the physics of particle transport, the transfer and distribution of radionuclides relies on a variety of fields ranging from ecology to biochemistry [24]. In this context it is important to emphasize that assessment tools for wildlife such as the ERICA Tool [14, 15] normally deal with transfer and uptake of radionuclides on the whole-body level. In the case of organ- or bone-seeking radionuclides, and especially for short range emitters, this simplification may inhibit a deeper understanding of radiation interactions at the scale of target organs or critical tissues, thus occluding a sophisticated understanding of the mechanisms leading to the development of observable effects. Although such considerations may be redundant for regulatory purposes rendering the whole-body approach appropriate for this particular application, the simplification is arguably insufficient for research.

2. Contrasting wildlife with state-of-the-art human dosimetry

Although conceptually equivalent, wildlife and human dosimetry differ in fundamental terms because whereas the radiological protection of humans is concerned with the individuals of a single species (and often under controlled or controllable conditions), protection goals for wildlife are usually aimed at whole populations from the several species that are present in and often freely roaming through a given heterogeneously contaminated ecosystem of interest [19, 20]. The radiological protection of humans is furthermore concerned with both deterministic and stochastic endpoints, whereas environmental impact assessments often are focused on deterministic endpoints relevant to population integrity. It follows that state-of-the-art methods in human dosimetry in practice are transferrable only to a subset of the species in an ecosystem (if at all), and that simpler methods must account for the remaining and majority of wildlife present [17]. To provide a consistent subset of species amenable to more detailed analysis, the ICRP defined in its publication 108 [27] a set of Reference Animals and Plants (RAPs). This approach has also been advocated by other agencies and authors [28]. Transfer parameters for the RAPs were subsequently discussed in publication 114 [29] and relevant exposure scenarios in publication 124 [30]. A proportion of the RAPs, such as rats and earthworms, are also used in laboratory dose-effect studies.

2.1 Computational phantoms

The introduction of RAPs follows the general approach of the ICRP towards the radiological protection of humans, which now revolves around the concept of a Reference Female and Reference Male [31]. These reference persons are density and composition resolved adult voxel phantoms designed for use with Monte Carlo radiation transport codes (such as EGSnrc [2], the MCNP-family [3] or Geant4 [4-6], see Table 2). A voxel phantom is a computational model of an organism [32] whose total volume has been subdivided into a set of equally sized cuboid volumes or voxels; each voxel belongs to a specified organ or tissue, and each organ or tissue has a specified density and elemental composition. Voxel phantoms for wildlife, and in particular for some of the reference animals, have been or are currently being developed; published results include phantoms of a mouse and a rat [33], a mouse [34, 35], a frog [36], two dogs [37], a crab [38] and a rainbow trout [39].

The creation of a voxel phantom generally starts out from tomographic whole-body data acquired through CT- or MR-scans on live or deceased individuals, or through visual photography of the sliced sections of a deceased individual [32]. Because voxel phantoms are built from tomographic data it is important to note that their geometries represent specific actual individuals, or specific virtual individuals if the phantoms have been adjusted (as is the case for the ICRP Reference Female and Reference Male [31]). The dosimetric quantities that are obtained from Monte Carlo simulations on a voxel phantom are therefore only to a degree representative of the doses other members of the same species would receive under the same exposure scenario.

This issue is currently being addressed by the introduction of so-called boundary representation (BREP) or hybrid phantoms [40, 41]. BREP phantoms are built, commonly from segmented tomographic data, e.g. as polygon mesh models or as representations utilizing so-called non-uniform rational B-splines (NURBS). This means that BREP phantoms consist of a set of surfaces, where the volumes bounded by each surface have a specified density and elemental composition. Most significantly, BREP phantoms differ from voxelized phantoms in that they are more easily adjustable. As such they can allow for rescaling e.g. to match different body shapes or organ masses, or they can be used for the study of time-dependent phenomena such as breathing motion. BREP phantoms are also better able to represent anatomically significant thin structures such as skin, which have dimensions below typical voxel dimensions of around $1 \times 1 \times 1$ cm^3 [42].

Some of the earliest BREP phantoms developed were the MOBY mouse phantom [43], and later the ROBY phantom of a rat [44]. BREP phantoms of mice, rats and a pig have been created by the IT'IS Foundation [45]. These phantoms were however primarily constructed for electromagnetic radiation dosimetry in the radiofrequency range [42], so that additional organ-specific data assignments are needed to make the phantoms suitable for use with Monte Carlo codes for ionizing radiation transport. A BREP phantom of a dog has also been created [26], with the primary intended use being dose assessments in preclinical radiopharmaceutical studies.

2.2 Computational phantoms in Monte Carlo codes

The major commonly known Monte Carlo codes for ionizing radiation transport, such as EGSnrc [2], the MCNP-family [3] or Geant4 [4-6], as well as others, can all construct or read voxelized models and transport radiation from either external or internal sources through such voxelized geometries [46-48]. In these general purpose codes it is irrelevant what organism or

object the voxelized geometries represent. This may not generally be the case for more specialized packages, which are not dealt with in this review.

The specific formats in which voxelized geometries or other computational phantoms must be represented will vary between code families. The concept of a computational phantom therefore encompasses a geometrical description plus a set of rules for assigning densities and elemental compositions to each geometrical subunit of the phantom; it does not imply that these data are represented in any particular format. A phantom must therefore be implemented for the specific Monte Carlo package utilized.

In this context it is worth noting that some codes can handle BREP phantoms directly, such as for instance Geant4 which can read polygon-mesh models [49]. Otherwise, voxel representations of BREP phantoms must be generated for implementation in Monte Carlo codes.

3. Basic principles of Monte Carlo codes

The term 'Monte Carlo' refers to methods in which random sampling from predefined probability distributions is used to numerically estimate the parameters characterizing a given process. In radiation transport, Monte Carlo simulations use theoretically calculated or experimentally measured differential cross sections and a set of random numbers to simulate N particle tracks.

3.1 The basic structure of a Monte Carlo run

A track begins when a primary particle is initialized with certain properties, such as energy and momentum, and then propagated in rectilinear steps through a given density and elemental composition resolved volume. The particle type, its properties and the material that it propagates through determine the so-called mean free path associated with each of the interactions i the particle can undergo. The probability for a particle to travel a distance l before an interaction of a specific type occurs can be modelled with an exponential probability distribution [5, 50]

$$p_i(l) = \exp\big(-f_i(l)\big),$$

where

$$f_i(l) = \int_0^l (1/\lambda_i(l'))dl'.$$

Here $\lambda_i(l')$ is the mean free path associated to interaction i over the distance from 0 to l'. The actual possible paths that a given particle may travel in the simulation before an interaction occurs is determined by generating random numbers $\eta_i \in (0,1)$ for each of the possible interactions, and using for instance the inverse-transform method to compute the corresponding distances as $l_i = -\ln \eta_i$ [5, 50]. The interaction process assigned the shortest l is then chosen and the actions associated to this process invoked. If the interaction deposits energy, this energy is recorded, and if the chosen interaction features scattered or secondary particles that should be tracked, their properties are established by using a new set of random numbers to draw values from the probability distributions for these properties.

To complete a full particle track for one primary particle, the above steps are subsequently repeated for all scattered or secondary particles, until the full energy of the original primary has been divided into a spatially resolved deposited fraction and an escaped fraction. The total deposited energy E_{dep} for a run is then incremented by the deposited fraction in the current track before a new primary particle is generated and tracked. A run consists of N such particle

tracks and when N grows, the variation in E_{dep} between runs, relative to the magnitude of E_{dep}, will decrease.

In addition to the deposited energy E_{dep}, there are a variety of other physical quantities that can be recorded in a Monte Carlo run. Simulations may thus provide data on processes that are hard to measure in a real world experiment. Monte Carlo simulations adapted for nano- and microdosimetry can furthermore simulate quantities with a very high spatial resolution. This feature may in particular be attractive to low dose research, where a macroscopic energy deposit averaged over a region that is comparatively large relative to the particle track likely is an inappropriate measure of both the directly induced damage and the biologically relevant delivered dose [51-53].

3.2 Physics models in Monte Carlo codes

From the above description, it is clear that generic Monte Carlo radiation transport codes in principle are equally applicable to simulations of radiation impinging on detectors, humans, radiation shields or wildlife. The limiting factors of Monte Carlo codes are commonly the types and energies of particles that can be accurately tracked, the physical interactions, materials and geometries that can be handled, the speed of the simulations and the ease of implementation for the user.

The major commonly known Monte Carlo codes for ionizing radiation transport largely handle the same physics processes of interest to wildlife dosimetry although the specific tools available for modelling these processes can and will vary between codes. Benchmarking or validation studies compare results from simulations implemented in different code families to each other, to theory and to experimental data [47, 54-58]. For wildlife dosimetry, benchmark studies of interest will typically be those that deal with low energy electromagnetic models [54, 58, 59], often in water targets. Large efforts are currently underway to extend and validate low energy as well as nano- and microdosimetry models in Geant4 [54, 55]. In particular, physics models validated for human dosimetry should be equally applicable to studies on wildlife or laboratory animals (see e.g. the EURADOS intercomparisons [60], the MCNP references [61], the Geant4 publication webpages [62], etc.). Intercomparisons between experimental doses for wildlife or laboratory animals and doses obtained via Monte Carlo simulations on phantoms would form a valuable addition to the current body of literature on wildlife dosimetry.

3.3 The Monte Carlo code 'world view'

The 'world view' of Monte Carlo codes determines what real world phenomena the codes can and cannot simulate. In this context it is important to be aware that the materials Monte Carlo codes see constitute volume resolved geometrical regions assigned different mean free paths, plus the boundaries between these regions. In particular, this implies that Monte Carlo codes only see homogenous and generally isotropic regions characterized by their mean free paths, and that no molecular, metallic or other structures exist. These latter features, which in real materials give rise to e.g. interference effects in scattered radiation fields, therefore normally do not exist in Monte Carlo codes for ionizing radiation transport. Simulation of atomic de-excitation via x-ray fluorescence and Auger electron emission is however possible [57, 63], and macroscopic models may be implemented in the codes for dealing with boundary effects such as reflection and refraction e.g. for optical photons.

It is furthermore worth noting that material excitations beyond atomic energy levels are not routinely considered in Monte Carlo codes for ionizing radiation transport. This implies that

e.g. infrared photons and molecular vibrations and rotations also are not generally considered. Other forms of simulation however exist, which specialize in e.g. dosimetry for infrared or radiofrequency electromagnetic fields. The input to radiofrequency codes are dielectric data [42] on relative permittivities and electrical conductivities rather than the densities and elemental compositions used for ionizing radiation transport codes.

4. Basic principles of computational phantoms

Computational phantoms are models that, although often intended for use with Monte Carlo codes for ionizing radiation transport, can and generally do exists without reference to any specific such code. This implies that the same geometrical model, for instance a BREP phantom, can be utilized for different purposes out of which ionizing radiation transport simulations may be one amongst many [32]. Good examples are the IT'IS phantoms [45], whose geometries have been filled with dielectric data for use in radiofrequency electromagnetic dosimetry, and with densities and elemental compositions for use in ionizing radiation transport.

4.1 From tomographic data to voxel phantoms

The creation of computational phantoms generally starts out from tomographic whole-body data. The data can be acquired through CT- or MR-scans on live or deceased individuals, or through visual photography of the sliced sections of a deceased individual. In a voxel phantom, the tomographic data are segmented into individual organs and residual tissues (for instance by the use of ImageJ [64]). Each organ or tissue then covers a specified set of voxels and when the phantom is intended for ionizing radiation transport, all the voxels in an organ or tissue are assigned the same density and elemental composition. In combination with the type and energy of the simulated incident radiation and any generated secondary particles, these properties determine the mean free paths discussed previously. The density and composition data can be acquired directly from measurements on the organs and tissues of a deceased individual, or they can be filled from pre-existing datasets.

The set of voxels which represent the segmented organs and residual tissues, in combination with the density and composition of each organ and tissue, comprises the traditional voxel phantom. Additional manipulations are needed in order to represent the phantom in a format which can be read by a given Monte Carlo code.

4.2 From voxel phantoms to BREP models

BREP phantoms are typically created from segmented tomographic data, which in essence are voxel phantom geometries. Following segmentation, the creation of a BREP phantom comprises the expression of each organ or body surface either as a polygonal mesh or as a smoothed surface, utilizing mathematical functions known as NURBS. Software tools are available for creating such surface representations (such as e.g. Rhinoceros [65]). The resulting BREP phantoms are scalable and in most cases, they must be re-voxelized for implementation in Monte Carlo codes [40, 41, 48].

4.3 Alternative methods

In addition to the above 'standard' methods for constructing computational phantoms, other methods exists that can achieve similar goals. Geant4 can e.g. read a DICOM format file [66], and use the values of each DICOM voxel to assign to these voxels a specified elemental composition before radiation transport is initiated.

In principle, any method which defines a phantom geometry with corresponding densities and elemental compositions can be thought of as a computational phantom. Similarly, all geometrical formats that result in sufficiently fast and accurate simulations can be considered suitable implementations of such phantoms in a given radiation transport code.

5. Basic principles of biodistribution

In the ERICA Tool, there are two main quantities that are used to assess doses to wildlife – these are the concentration ratios or CRs, and the previously discussed dose conversion coefficients or DCCs. Whereas the DCCs are derived ad hoc from Monte Carlo simulations applied to simple shapes, the CRs are purely empirical, or extrapolated from empirical data. Allometric modelling can additionally provide semi-empirical predictions of CRs [67]. Uncertainties or data gaps in the CRs are however a strong limiting factor for the accuracy of dose evaluations to wildlife on the whole-body level, although efforts have been made to account for these limitations be selecting high percentile transfer parameters [21]. The situation is compounded by the fact that knowledge on the uptake of radionuclides by wildlife often stems from human food chain studies, which have considered the uptake to specific organs or tissues in species relevant to human consumption rather than to the whole organism. Methods have however been proposed for deriving whole-body CRs from tissue or organ specific data [68].

5.1 Spatially heterogeneous activity concentrations

The concept of whole-body homogenous activity concentrations that is adopted in environmental management may be appropriate for some radionuclides but quite unsuitable for others, such as organ- or bone-seeking radionuclides (e.g. iodine-131 in the thyroid [69] or strontium-90 in bones [70]). The biodistribution of radionuclides can therefore be a central topic for (refined) assessments or in research, when the specific pathways to potential biological harm are of interest. The degree by which such data can be extrapolated between different exposure scenarios (e.g. from controlled exposures to exposures of free-roaming wildlife [71]) will depend on several factors, out of which a central one is the physiochemical form of the contaminants in the different exposure scenarios [72]. However, if the biodistribution at a given point in time is known, most Monte Carlo codes for ionizing radiation transport can be adapted to yield dose maps based on such activity concentration mappings.

5.2 Temporally heterogeneous activity concentrations

The situation however changes if the biodistribution of radionuclides cannot be approximated as a time-independent map onto an organism with a fixed geometry. Such problems are much harder to handle in simulations, both from a conceptual and computational resources standpoint. Simple computational phantoms for a small set of geometries associated with different life stages of a plant have been demonstrated [73], but are already at this level quite work intensive. The problem is further aggravated by the fact that in nature, some of the potentially most damaging events are nuclear accidents, after which activity concentrations will vary with time [74], both as the initial release is dispersed in the environment and as short-lived species decay. Following the Fukushima accident attempts were made [75] to account for these rapidly changing concentrations in the environment in the early stages of releases through the application of kinetic models. Furthermore, attention was given to the limitations introduced to the assessments by not considering biodistributions. In particular thyroid doses from inhalation of iodine-131 by mammals may be an important component of

exposure in the intermediate phase of an accident, but considering such exposures explicitly is far from straightforward [75].

5.3 Exposure to low and chronic activity concentrations

There are however also uncertainties associated with how an organism, even if hypothetically existing in an environment with a stationary activity concentration, will display a time-varying and history dependent response, especially to low, chronic doses. This is a fundamental and charged issue in the study of radiation effects in both humans and wildlife. The fact that detection of radiation effects at this level is difficult [76, 77], is nevertheless a clear sign that the associated risks (or benefits) are likely to be low. For wildlife dosimetry, it is in particular important to recognize that in (very) low dose research, macroscopic doses (either whole-body or whole organ doses) are inappropriate for a mechanistic understanding of effects and at least some considerations on the level of nano- and microdosimetry (track structures [53]) may be merited.

6. Precision and accuracy in wildlife dosimetry

The concepts of accuracy and precision are crucial in all quantitative sciences and present a particularly pertinent argument in computational dosimetry. Precision in this context refers to the repeatability of measurements or simulation outcomes (or data scatter), whereas accuracy refers to the agreement of measured or simulated values with the 'true value' [25]. Computational phantoms in conjunction with Monte Carlo codes typically offer great precision in computing absorbed fractions and also great accuracy in simulating absorbed fractions for specific, 'simple' benchmarking geometries [54, 56, 58, 78], for which precise measurements are possible. Relatively good agreement between simulated and measured doses is also achieved for specific actual or virtual individuals represented by phantoms [47, 79], wherein differences may be attributed to uncertainties on detector responses and calibration, a lack of agreement between the simulated system and the real system, as well as on the physics models chosen in the simulations. When results from a given computational phantom of an individual are used to estimate doses to another member of the same species (or even another species), accuracy falls further [41]. The use of one anatomically correct phantom for estimation of absorbed fractions to a range of anatomically dissimilar individuals therefore inherently introduces inaccuracies [32]. To a degree this problem can be addressed by the use of scalable BREP phantoms [41].

Many other sources of inaccuracy however exist in wildlife dosimetry beyond those that directly pertain to phantoms and radiation transport simulations. Examples particularly relevant for wildlife dosimetry include issues related to the use of concentrations ratios, as well as field specific concerns such as roaming patterns, heterogeneous landscape contaminations, the physiochemical form of contaminants, biological half-lives, life stages of the organisms, and others. In general, these inaccuracies or uncertainties on quantitative parameters are also more severe than those associated with the computational dosimetry, while further qualitative uncertainties may also be present, e.g. in linking doses to effects. In a regulatory management context, it is therefore reasonable to conclude that the routine use of e.g. voxel phantoms in dose evaluations is not warranted at this time, because the excess precision of these models is unnecessary in a context where the overall accuracy, including the accuracy on dose-effect relations, anyway is low. This may be particularly true for population- or ecosystem-level assessments, where very large knowledge gaps exist.

The need for accurate dosimetry is much more pronounced in a research setting, where either exposure conditions are controlled or at least more closely monitored. In such contexts, the

use of realistic anatomical models for computational dosimetry may be warranted or even necessary. Studies involving internal exposure scenarios from heterogeneously distributed radionuclides are particularly dependent upon realistic models for calculation of self-absorbed fractions as well as organ-to-organ crossfire. This is especially true for situations in which the range of emitted particles is on the order of the dimensions of the organs of interest. In low dose research, it may furthermore be inappropriate to only deal with macroscopic, average doses and microdosimetry simulations along with probabilistic modelling may in such cases be appropriate.

The question of whether current dosimetric models and methodology for wildlife are fit for purpose was recently discussed at a STAR workshop held in Madrid in June, 2014 [80]. During the discussions it was generally agreed that the criteria by which fit for purpose can be demonstrated, will depend upon the aims of a given dose assessment. For wildlife dosimetry, such assessments may be broadly divided into situations of environmental management (predicting possible doses for planned exposure situations), environmental assessment (assessing actual doses e.g. for existing exposure situations when measurement data may be available), and research, with each incremental step requiring more realistic dosimetric models in order to meet the associated aims. There is concurrently also a gradient in the number of organisms considered across these categories, such that whereas environmental management may refer to whole ecosystems, research and especially laboratory research most often deals with small sets of individuals of a single species. It is here appropriate to highlight the fact that extrapolations between individual-level effects in the laboratory and individual- or population-level effects in nature are not trivial [20, 71]. This is also true for the dosimetry, so that whereas individual-level dose assessments may be appropriate in research, they will typically both be unfeasible and unnecessary in environmental management. The question of whether probabilistic models for doses and effects should be integrated in assessments was raised at the STAR workshop [80]. Although the issue was not settled, there was general agreement that different assessment categories will require different methodologies for the dosimetry.

In the first of these categories, namely environmental management, where aims are typically set at the political level (e.g. protection of ecosystems), the role of dosimetric evaluations are normally to determine conservative criteria for whether doses or dose rate screening bands or values are exceeded in a specific exposure scenario or not. The simple models employed for instance in the ERICA Tool are here likely fit for purpose, and the main challenges lie elsewhere in relation to CRs, life stages and other factors.

In environmental assessments, an existing exposure situation is present in the environment and the role of dosimetric evaluations in this case might be to determine doses based on measured or estimated activity concentrations. Here simple dosimetric models could be sufficient, although if biodistribution data are available with for instance an organ-specific resolution, then the computational dosimetry should ideally be tailored to match this resolution.

In research finally, be it in field or under laboratory conditions, the role of dosimetric evaluations can be considered to be the determination of doses and dose rates to at least the degree of accuracy required by the corresponding effects data. Note however, that such effects data could refer either to a set of individuals or to a population as a whole. Dosimetric assessments should therefore be tailored accordingly.

Throughout these three broad categories of management, assessment and research, it can in conclusion be argued that if methods for dosimetry are available to estimate doses with the

required precision and accuracy and without excess precision where accuracy anyway is low, then the methods are fit for purpose. What the required accuracy and precision should be at each category however remains a point for consideration that may and likely will change as overall aims are altered or as new knowledge on effects, uptake and biodistribution are accumulated.

7. Tables

Table 1: Overview of EC funded projects on radiation protection of the environment, including a related Network of Excellence on low dose effects (DOREMI). Further information can be obtained through the EC Community Research and Development Information Service (CORDIS), as indicated in the listed references.

Acronym	CORDIS info	Project title	
EPIC	FP5-INCO 2 Cost-Sharing Contracts 2000-2003	Environmental Protection from Ionising Contaminants in the Arctic	[81]
FASSET	FP5-EAECTP C Cost-Sharing Contracts 2000-2003	Framework for Assessment of Environmental Impact	[82]
ERICA	FP6-EURATOM-RADPROT Specific Targeted Research Project 2004-2007	Environmental Risk from Ionising Contaminants: Assessment and Management	[83]
PROTECT	FP6-EURATOM-RADPROT Coordination Action 2006-2008	Protection of the Environment from Ionising Radiation in a Regulatory Context	[8]
DOREMI	FP7-EURATOM-FISSION Networks of Excellence 2010-2015	Low Dose Research towards Multidisciplinary Integration	[84]
STAR	FP7-EURATOM-FISSION Networks of Excellence 2011-2015	Strategy for Allied Radioecology	[1]
COMET	FP7-EURATOM-FISSION CPCSA 2013-2017	Coordination and Implementation of a Pan-European Instrument for Radioecology	[22]

Table 2: Overview of Monte Carlo codes for ionizing radiation transport. The list is focused on the most common code families featured in the peer-reviewed literature from the 2000s onwards, and is not exhaustive. In code families with successive releases only the newest release is listed. Information on previous releases and derived daughter codes can be found in the listed references.

Mother code	Language	Platforms	License	Daughter codes	Inherits
MCNP6 [3]	Fortran 90	Cross-platform	Proprietary, not open source		MCNP5 MCNPX
Geant4 [4-6]	C++	Cross-platform	Free non-commercial, open source	GATE [85, 86] GAMOS [87, 88] TOPAS [89, 90]	Geant3 PENELOPE 2008 [91]
EGSnrc [2] (also other EGS codes, see e.g. [92])	Fortran, C, C++	Cross-platform	Free non-commercial, open source		
PENELOPE	Fortran 77, Fortran 90 compatible	Cross-platform	Free non-commercial, open source		
FLUKA [93-95]	Fortran	Linux	Free non-commercial, open source		

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