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Voxel modeling of rabbits for use in radiological dose rate calculations

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ABSTRACT

Radiation dose to biota is generally calculated using Monte Carlo simulations of whole body ellipsoids with homogeneously distributed radioactivity throughout. More complex anatomical phantoms, termed voxel phantoms, have been developed to test the validity of these simplistic geometric models. In most voxel models created to date, human tissue composition and density values have been used in lieu of biologically accurate values for non-human biota. This has raised questions regarding variable tissue composition and density effects on the fraction of radioactive emission energy absorbed within tissues (e.g. the absorbed fraction - AF), along with implications for age-dependent dose rates as organisms mature. The results of this study on rabbits indicates that the variation in composition between two mammalian tissue types (e.g. human vs rabbit bones) made little difference in self-AF (SAF) values (within 5% over most energy ranges). However, variable tissue density (e.g. bone vs liver) can significantly impact SAF values. An examination of differences across life-stages revealed increasing SAF with testis and ovary size of over an order of magnitude for photons and several factors for electrons, indicating the potential for increasing dose rates to these sensitive organs as animals mature. AFs for electron energies of 0.1, 0.2, 0.4, 0.5, 0.7, 1.0, 1.5, 2.0, and 4.0 MeV and photon energies of 0.01, 0.015, 0.02, 0.03, 0.05, 0.1, 0.2, 0.5, 1.0, 1.5, 2.0, and 4.0 MeV are provided for eleven rabbit tissues. The data presented in this study can be used to calculate accurate organ dose rates for rabbits and other small rodents; to aide in extending dose results among different mammal species; and to validate the use of ellipsoidal models for regulatory purposes.

1. Introduction

Voxel models allow for organ dose rate calculations and the consideration of organ-to-organ contributions to dose. Generally, radiation dose to non-human biota from environmental source terms are calculated using dose conversion factors (DCFs), which are absorbed dose rates per unit activity concentration ($\mu Gy\ d^{-1}$ per $Bq\ kg^{-1}$). The current method for calculating DCFs recommended by the International Commission on Radiological Protection (ICRP), and implemented in the ERICA Integrated Approach (Brown et al., 2008), utilizes Monte Carlo simulations of an ellipsoidal organism geometry with homogeneously distributed radioactivity throughout (ICRP, 2008; Gómez-Ros et al., 2008). Current research efforts are focused on creating voxel phantoms, which include distinct organs and tissues, to determine the degree of uncertainty introduced when using the simplifying assumptions of ellipsoidal shapes and homogeneous radionuclide distributions (see Ruedig et al., 2014a for details) and to evaluate if voxel DCFs are consistent with those from the simple models developed by the ICRP (ICRP, 2008). Voxel models completed to date and utilized in an environmental context include a crab, flatfish, trout, rat, mouse, and frog (Caffrey and Higley, 2013; Caffrey, 2012; Ruedig et al., 2014b; Stabin et al., 2006; Kinase, 2008). Additional voxel models available to interested researchers include, but are not limited to, Digimouse, and two different canine models (Dogdas et al., 2007; Padilla et al., 2008; Kramer et al., 2012). Additionally, there are two "compromise" options between the basic single ellipsoid models and voxel models that are worth mentioning. The first is the stylized model. In stylized models, pertinent organs are included as ellipsoids (see Martinez et al., 2014 for an example of a stylized model). This has the advantage of allowing researchers to calculate dose to sensitive organs, while still maintaining much of the simplicity of using ellipsoidal models. The second is a technique developed by Gómez-Ros et al. (2008) wherein organ dose rates can be obtained by multiplying whole body dose rates by a ratio of the whole body mass to the mass of the organ of interest.

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Voxel models are particularly useful in scenarios in which the radionuclides disproportionately partition into the specific organs/tissues of mammals after internalization (Yankovich et al., 2010; ICRP, 1986; ICRP, 1993). For example, proportionally high accumulation of plutonium in bone (83% ± 10%) compared to that in liver (6% ± 6%) of mammalian wildlife at the former British nuclear weapons test site at Maralinga, Australia (Johansen et al., 2015). These data for wildlife contrast with that from mainly laboratory experiments summarized by the ICRP (45–50% bone, 30–45% liver) (ICRP, 1986), and organ-specific dose models may provide insight into the dose implications of the higher accumulation in bone.

In this study, adult and juvenile rabbit models were created to answer longstanding questions regarding voxel modeling. First, the models were used to examine the effects of variable tissue composition and density on absorbed fraction (AF) values to determine the validity of using human data in non-human mammalian models. Second, the models were used to examine variations across life-stages. Adult versus juvenile self-AFs (SAF; source and target are the same organ/tissue) were compared across all major organ systems. An in-depth analysis was performed on internal electron emitters in testes and ovaries of varying sizes to elucidate the effects of organ size on SAF value.

2. Materials and methods

Two black-tailed jackrabbits (*Lepus californicus)* were obtained post-mortem, an adult male weighing approximately 2 kg (4.5 lb), and a juvenile female weighing about 0.8 kg (1.8 lb). Computed tomography (CT) scans were conducted at the Oregon State University School of Veterinary Medicine on a Toshiba Aquillion 64 slice machine. Axial plane images were used for image reconstruction for both specimens. Voxel dimensions of the adult were 0.679 mm × 0.679 mm × 2 mm, resulting in a 3D pixel matrix of 276 rows × 276 columns × 202 planes. Voxel dimensions of the juvenile were 0.395 mm × 0.395 mm × 2 mm, resulting in a 3D pixel matrix of 268 rows × 268 columns × 141 planes. Fig. 1 depicts adult rabbit anatomy, shown on a sagittal slice of the CT scan.

Voxel phantom geometry is created via organ segmentation performed on the axial CT scan slices. Identifiable organs were

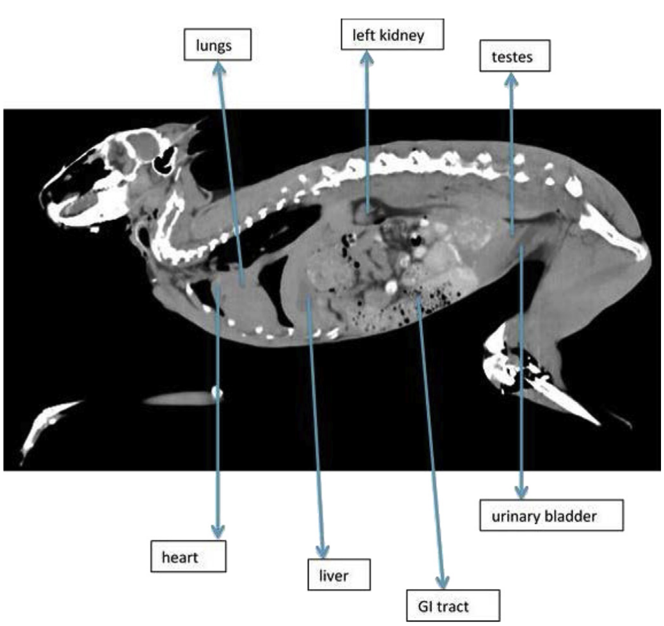

Fig. 1. Adult Lepus californicus anatomy shown on a sagittal CT scan slice.

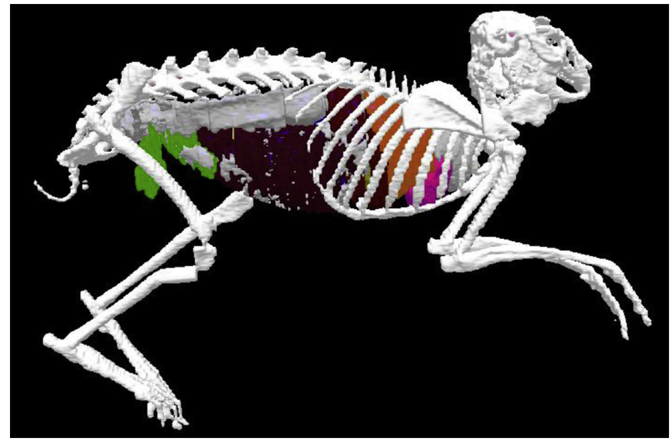

Fig. 2. 3D rendering of adult rabbit model from 3D Doctor.

manually contoured using 3D Doctor Software,[1] and a 3D model was created (see Fig. 2).

Identifiable organs included the following for both the adult and the juvenile: bone, bone marrow, liver, gallbladder, testes/ovaries, lungs, kidneys, heart, gastrointestinal (GI) tract, stomach contents, feces, brain, fat, blood, muscle tissue (not shown in Fig. 2), and skin (not shown in Fig. 2; see Table 1 for organ segment details). The urinary bladder of the adult specimen was full and therefore visible on the CT scan, and was also segmented. Segment data is exported from 3D Doctor via a boundary file. The boundary file specifies the start and stop points of each contoured organ or tissue on each slice of the CT scan. This information is imported into Lattice Tool[2] (also known as Voxelizer) (Kramer et al., 2010), and converted into a repeated structures lattice format for use in Monte Carlo N-Particle (MCNP) simulations (X-5 Monte Carlo Team, 2008). Once converted to MCNP format, tissue density and composition information can be added. Previous voxel models have utilized human tissue compositions due to the lack of available organism tissue compositions (Kinase, 2008; Ulanovsky and Pröhl, 2006; Caffrey and Higley, 2013). In order to obtain realistic organism tissue composition and density, and to avoid adding additional uncertainty to the dose calculations, both rabbits were dissected post CT scans, and an elemental analysis performed on selected organs. Dissection technique details are available as Supplementary Material.

The displacement technique used in this work was developed specifically for this study, drawing information from a study by Webb (1990) that measured the density of benthic fish organs. A Pyrex graduated cylinder was filled with plain water. Organs were carefully lowered and completely submerged into water using tweezers, and gently massaged as needed to remove air bubbles. Water displacement was recorded. This was repeated for all organs excluding the GI tract, stomach contents, and feces of both specimens, the juvenile spleen, and the adult urinary bladder. For muscle density calculations, a large section of the inner thigh of each rabbit was used for displacement measurements. Density calculated for muscle samples was assumed to apply to the whole body muscle area (Webb, 1990). The left femur of each specimen was used to obtain a reasonable value for rabbit bone density.

Organ composition was determined using the elemental analyzer facility in the Oregon State University College of Earth,

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