Determining organ dose conversion coefficients for external neutron irradiation by using a voxel mouse model

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ABSTRACT

A set of fluence-to-dose conversion coefficients has been calculated for neutrons with energies <20 MeV using a developed voxel mouse model and Monte Carlo N-particle code (MCNP), for the purpose of neutron radiation effect evaluation. The calculation used 37 monodirectional monoenergetic neutron beams in the energy range $10^{-9}$ MeV to 20 MeV, under five different source irradiation configurations: left lateral, right lateral, dorsal–ventral, ventral–dorsal, and isotropic. Neutron fluence-to-dose conversion coefficients for selected organs of the body were presented in the paper, and the effect of irradiation geometry conditions, neutron energy and the organ location on the organ dose was discussed. The results indicated that neutron dose conversion coefficients clearly show sensitivity to irradiation geometry at neutron energy below 1 MeV.

KEYWORDS: neutron dose, organ dose conversion coefficients, Monte Carlo, voxel mouse model

INTRODUCTION

One of the important tasks in radiation effect research is to estimate organ dose for the purpose of obtaining the dose–effect relation. Since organ dose is not directly measurable, organ dose conversion coefficients are usually employed to get organ dose by linking the measurable quantities, e.g. fluence and air kerma, with organ dose. In recent years, many research groups [1–12] have utilized the mouse model (either mathematical model or image-based model) and Monte Carlo simulation to get a series of photon or electron dose conversion coefficients for internal and external irradiation. Currently, except for the published neutron dose conversion coefficients based on human models that are used for radiation protection purposes, there are no published neutron dose conversion coefficients for experimental animals that are used in neutron radiation effect research. Therefore, it is necessary to obtain sets of neutron organ dose conversion coefficients for experimental animals (such as monkey, rat, mouse, etc.) that are used in neutron radiation effect research.

The aim of this study is to present a set of neutron fluence-to-dose conversion coefficients based on the developed voxel mouse model in the energy range of $10^{-9}$ to 20 MeV, under five ideal irradiation conditions, using the Monte Carlo N-particle code (MCNP). Meanwhile, the effect of irradiation geometry conditions, neutron energy and the organ locations on the organ dose will be discussed.

MATERIALS AND METHODS

Original image and processing

The original consecutive section images used for the construction of the voxel mouse model were provided by the University of Southern California, LA. Briefly, the process of obtaining these images was as follows: first, a normal 28-g male mouse, together with carboxyl methyl cellulose (CMC) in a box, was frozen to form a block; then, the frozen block was sectioned along the coronal plane with a milling machine with an accuracy of 50 µm; finally, each acquired slice was photographed with a high-resolution digital camera. As a result, 418 images were obtained in JPEG format, with a resolution of $1704 \times 2560$ pixel and a size of $38.8 \times 38.8$ µm$^2$ per pixel.

Registration of the 418 images was made through geometric transformation according to the fiducial markers in each one. In consideration of the efficiency and accuracy of Monte Carlo simulation...
calculation, the size of each voxel of the model should not be too small and the total number of voxels should be moderate. Therefore, every fourth-slice image was selected to generate the 50 µm × 4 = 0.2 mm thickness along the coronal plane; thus, 100 images were applied. Then, the external useless pixels outside the body were removed to reduce voxels; organs or tissues were segmented manually and filled with specific color with the software Photoshop CS 8.0. The segmented organs comprised skin, bone, eye, brain, heart, bladder, testicle, stomach, pancreas, spleen, liver, kidneys, adrenal glands, lungs and muscle. Finally, each segmented slice image was sampled to a pixel size of 0.2 × 0.2 mm² through bicubic interpolation in the batch mode of software ACDsee 10, with a resolution of 190 × 496 pixel. To observe the effects of registration and the segment, the 3D mouse model was built via volume rendering with software Visualization Toolkit [13] (VTK, an open source, freely available software system for 3D computer graphics, image processing, and visualization), as Fig. 1 shows.

Implementation of mouse model in MCNP

For the purpose of Monte Carlo simulation, by using a program written in C language, as well as the repeated structure algorithm in MCNP code, each voxel in the model was given specific physical properties, i.e. elementary composition and density, which were obtained from the No. 46 Report of the International Commission on Radiation Units and Measurements (ICRU) [14]. With the picture-drawing feature of MCNP, the image of the 70th slice of the voxel mouse model in the front view was derived and shown in Fig. 2.

Monte Carlo simulation

MCNP [15] is a general purpose Monte Carlo code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport. MCNP uses continuous energy nuclear and atomic data libraries, the evaluated nuclear data file (ENDF) system, the evaluated nuclear data library (ENDL) and the activation library (ACTL). Nuclear data tables exist for neutron interactions, neutron-induced photons, photon interactions, neutron dosimetry or activation, and thermal particle scattering. Except for neutron-induced photons, protons and other particles generated by neutron interactions were treated as being locally deposited. Photon and electron data are atomic rather than nuclear in nature. Photon interaction tables exist for all elements from Z = 1 to Z = 94 and for coherent and incoherent scattering, photoelectric absorption with the possibility of fluorescent emission, and pair production.

In this study, Monte Carlo simulations were performed using MCNP 4C to calculate the organ dose. The incident neutrons were assumed to be monoenergetic beams with energies from 10⁻⁹ to 20 MeV. The five ideal irradiation geometric conditions are respectively: left lateral (LL), right lateral (RL), dorsal–ventral (DV), ventral–dorsal (VD) and isotropic (ISO, the mouse was irradiated uniformly in all directions by the external neutron source), as Fig. 3 shows. The energy depositions in tissue or organs from neutrons and secondary photons were determined using the *F6 tally (energy deposition in units of jerks/g), in which the organ absorbed dose was actually estimated in the kerma approximation. The results were then normalized to the units of incident neutron fluence in order to express the results in the form of fluence-to-dose conversion coefficients (in the units of pGy cm²). ENDF/B-VI.0 and ENDF/B-VI.1 of the ENDF were chosen for the simulation. The S(a,b) scattering treatment for light water at 300 K was applied to take into account the effects of chemical binding and crystal structure for incident neutron energies below ~4 eV. In consideration of the requirement of precision and the acceptable calculation time, the cutoff energy for neutrons and photons was set as 0.0 keV and 1 keV, respectively. To keep the statistical error within 5%, the total number of histories for each simulation was set at 5 × 10⁷ to 1 × 10⁸, depending on the organ and neutron energy.
RESULTS
Voxel mouse model
The voxel mouse model was comprised of a total of 3 270 018 voxels with a size of 0.2 × 0.2 × 0.2 mm$^3$ and contained most of the main organs or tissues of the mouse. Some organs and tissues, such as intestines, which were not included in the model because they were not clearly distinguished, were replaced by muscles and soft tissues. The mass of each organ is equal to the number of voxels times the voxel volume times the organ density. Table 1 shows the mass and density of selected organs and tissues. The total mass of the voxel mouse model is 26.923 g, ~1 g less than the real mouse. This is possibly due to the organ density difference between the model and the real mouse, as well as the unavoidable segmentation discrepancy of the organ or tissues.

Organ dose conversion coefficients
The calculated neutron fluence-to-dose conversion coefficients (with the relative error in parentheses) are presented in Tables 2–5 for some selected organs at some energy points. The statistical uncertainties of the calculation results are <3% in most cases, except for some organs such as pancreas and eye, in which the uncertainties are <5% because of the relatively small mass.

Table 1. Organ density and mass in the mouse model

| Organ             | Voxel number | Density (g cm$^{-3}$) | Mass (g) |
|-------------------|--------------|-----------------------|----------|
| Skin              | 440 525      | 1.09                  | 3.841    |
| Skeleton          | 162 540      | 1.4                   | 1.820    |
| Eye               | 486          | 1.07                  | 0.004    |
| Brain             | 53 074       | 1.04                  | 0.442    |
| Heart             | 25 682       | 1.06                  | 0.218    |
| Bladder wall      | 8215         | 1.04                  | 0.068    |
| Bladder content   | 16 585       | 1.03                  | 0.137    |
| Testis            | 16 351       | 1.04                  | 0.136    |
| Stomach wall      | 9818         | 1.05                  | 0.082    |
| Stomach contents  | 21 136       | 1.02                  | 0.172    |
| Spleen            | 15 596       | 1.06                  | 0.132    |
| Pancreas          | 4980         | 1.04                  | 0.041    |
| Liver             | 237 136      | 1.06                  | 2.010    |
| Kidneys           | 56 888       | 1.05                  | 0.478    |
| Adrenal glands    | 518          | 1.05                  | 0.004    |
| Lungs             | 45 975       | 0.26                  | 0.096    |
| Muscle/soft tissue| 2 139 651    | 1.0                   | 17.117   |
| Others            | 14 862       | 1.05                  | 0.125    |
| Total             | 3 270 018    |                       | 26.923   |
### Table 2. Absorbed dose per unit neutron fluence for skin under five irradiation conditions

| Energy (MeV) | Organ dose conversion coefficients in various geometries $D_T/\Phi$ (pGy cm$^{-2}$) |
|--------------|---------------------------------------------------------------------------------|
|              | LL (pGy cm$^{-2}$) | RL (pGy cm$^{-2}$) | DV (pGy cm$^{-2}$) | VD (pGy cm$^{-2}$) | ISO (pGy cm$^{-2}$) |
| $1.0 \times 10^{-9}$ | 0.454 (0.44) | 0.474 (0.44) | 0.765 (0.33) | 0.686 (0.32) | 0.495 (1.02) |
| $1.0 \times 10^{-8}$ | 0.435 (0.47) | 0.449 (0.46) | 0.738 (0.34) | 0.683 (0.33) | 0.488 (1.08) |
| $1.0 \times 10^{-7}$ | 0.407 (0.50) | 0.416 (0.49) | 0.648 (0.39) | 0.614 (0.37) | 0.450 (1.16) |
| $1.0 \times 10^{-6}$ | 0.372 (0.55) | 0.375 (0.54) | 0.521 (0.46) | 0.504 (0.45) | 0.401 (1.33) |
| $1.0 \times 10^{-5}$ | 0.335 (0.60) | 0.336 (0.59) | 0.465 (0.51) | 0.451 (0.50) | 0.356 (1.45) |
| $1.0 \times 10^{-4}$ | 0.309 (0.62) | 0.312 (0.62) | 0.434 (0.53) | 0.418 (0.52) | 0.329 (1.51) |
| $1.0 \times 10^{-3}$ | 0.332 (0.51) | 0.332 (0.50) | 0.462 (0.43) | 0.441 (0.43) | 0.353 (1.22) |
| $1.0 \times 10^{-2}$ | 0.681 (0.19) | 0.677 (0.19) | 0.940 (0.16) | 0.829 (0.18) | 0.733 (0.44) |
| $1.0 \times 10^{-1}$ | 4.567 (0.05) | 4.539 (0.05) | 5.938 (0.04) | 5.369 (0.04) | 4.887 (0.13) |
| $5.0 \times 10^{-1}$ | 13.102 (0.05) | 13.038 (0.05) | 15.424 (0.04) | 14.614 (0.04) | 13.647 (0.12) |
| $1.0 \times 10^{0}$ | 19.244 (0.05) | 19.162 (0.05) | 21.801 (0.04) | 20.951 (0.04) | 19.839 (0.12) |
| $5.0 \times 10^{0}$ | 43.139 (0.07) | 43.030 (0.07) | 45.785 (0.07) | 44.940 (0.07) | 43.683 (0.19) |
| $1.0 \times 10^{1}$ | 50.497 (0.06) | 50.410 (0.06) | 52.643 (0.06) | 51.998 (0.06) | 51.009 (0.16) |
| $1.5 \times 10^{1}$ | 61.820 (0.11) | 61.698 (0.11) | 63.920 (0.10) | 63.170 (0.10) | 62.320 (0.27) |
| $2.0 \times 10^{1}$ | 68.691 (0.13) | 68.582 (0.13) | 70.638 (0.13) | 69.879 (0.13) | 69.070 (0.33) |

LL = left lateral, RL = right lateral, DV = dorsal–ventral, VD = ventral–dorsal, ISO = isotropic.

### Table 3. Absorbed dose per unit neutron fluence for bone under five irradiation conditions

| Energy (MeV) | Organ dose conversion coefficients in various geometries $D_T/\Phi$ (pGy cm$^{-2}$) |
|--------------|---------------------------------------------------------------------------------|
|              | LL (pGy cm$^{-2}$) | RL (pGy cm$^{-2}$) | DV (pGy cm$^{-2}$) | VD (pGy cm$^{-2}$) | ISO (pGy cm$^{-2}$) |
| $1.0 \times 10^{-9}$ | 0.361 (0.68) | 0.392 (0.68) | 0.824 (0.48) | 0.736 (0.50) | 0.481 (1.59) |
| $1.0 \times 10^{-8}$ | 0.429 (0.70) | 0.457 (0.67) | 0.901 (0.49) | 0.813 (0.50) | 0.543 (1.61) |
| $1.0 \times 10^{-7}$ | 0.489 (0.70) | 0.518 (0.70) | 0.842 (0.55) | 0.791 (0.55) | 0.555 (1.68) |
| $1.0 \times 10^{-6}$ | 0.472 (0.77) | 0.492 (0.76) | 0.671 (0.65) | 0.655 (0.64) | 0.480 (1.78) |
| $1.0 \times 10^{-5}$ | 0.430 (0.85) | 0.444 (0.84) | 0.583 (0.72) | 0.582 (0.71) | 0.440 (2.05) |
| $1.0 \times 10^{-4}$ | 0.387 (0.91) | 0.394 (0.89) | 0.516 (0.76) | 0.524 (0.77) | 0.385 (2.21) |
| $1.0 \times 10^{-3}$ | 0.363 (0.85) | 0.374 (0.84) | 0.489 (0.71) | 0.490 (0.71) | 0.363 (2.02) |
| $1.0 \times 10^{-2}$ | 0.296 (0.78) | 0.310 (0.76) | 0.411 (0.64) | 0.399 (0.68) | 0.311 (1.98) |
| $1.0 \times 10^{-1}$ | 1.557 (0.14) | 1.611 (0.14) | 2.025 (0.12) | 1.907 (0.12) | 1.593 (0.35) |
| $5.0 \times 10^{-1}$ | 4.707 (0.09) | 4.788 (0.09) | 5.458 (0.08) | 5.298 (0.08) | 4.736 (0.23) |
| $1.0 \times 10^{0}$ | 7.028 (0.10) | 7.101 (0.10) | 7.839 (0.08) | 7.681 (0.08) | 7.046 (0.24) |
| $5.0 \times 10^{0}$ | 18.752 (0.22) | 18.815 (0.21) | 19.776 (0.21) | 19.570 (0.21) | 18.841 (0.54) |
| $1.0 \times 10^{1}$ | 22.712 (0.17) | 22.790 (0.17) | 23.518 (0.16) | 23.442 (0.16) | 22.871 (0.44) |
| $1.5 \times 10^{1}$ | 30.971 (0.30) | 31.158 (0.30) | 31.913 (0.29) | 31.912 (0.29) | 31.094 (0.74) |
| $2.0 \times 10^{1}$ | 36.959 (0.35) | 37.184 (0.35) | 37.887 (0.34) | 37.969 (0.34) | 36.808 (0.85) |

LL = left lateral, RL = right lateral, DV = dorsal–ventral, VD = ventral–dorsal, ISO = isotropic.
### Table 4. Absorbed dose per unit neutron fluence for brain under five irradiation conditions

| Energy (MeV) | LL | RL | DV | VD | ISO |
|--------------|----|----|----|----|-----|
| $1.0 \times 10^{-9}$ | 0.391 (1.25) | 0.415 (1.32) | 0.976 (0.88) | 0.552 (1.00) | 0.459 (2.79) |
| $1.0 \times 10^{-8}$ | 0.477 (1.23) | 0.495 (1.19) | 1.011 (0.91) | 0.641 (0.97) | 0.557 (3.11) |
| $1.0 \times 10^{-7}$ | 0.521 (1.31) | 0.541 (1.32) | 0.837 (1.05) | 0.655 (1.08) | 0.501 (2.93) |
| $1.0 \times 10^{-6}$ | 0.478 (1.50) | 0.478 (1.44) | 0.605 (1.29) | 0.553 (1.30) | 0.452 (3.51) |
| $1.0 \times 10^{-5}$ | 0.421 (1.62) | 0.414 (1.61) | 0.511 (1.44) | 0.493 (1.44) | 0.373 (3.81) |
| $1.0 \times 10^{-4}$ | 0.381 (1.74) | 0.378 (1.67) | 0.469 (1.52) | 0.452 (1.48) | 0.358 (4.61) |
| $1.0 \times 10^{-3}$ | 0.423 (1.51) | 0.413 (1.43) | 0.513 (1.25) | 0.475 (1.31) | 0.370 (3.31) |
| $1.0 \times 10^{-2}$ | 0.741 (0.65) | 0.738 (0.59) | 0.953 (0.54) | 0.724 (0.66) | 0.626 (1.11) |
| $1.0 \times 10^{-1}$ | 5.216 (0.21) | 5.226 (0.21) | 6.182 (0.17) | 5.045 (0.19) | 4.647 (0.55) |
| $5.0 \times 10^{-1}$ | 15.068 (0.20) | 15.070 (0.20) | 16.261 (0.17) | 14.902 (0.17) | 13.915 (0.51) |
| $1.0 \times 10^{0}$ | 21.816 (0.20) | 21.840 (0.20) | 22.998 (0.17) | 21.714 (0.17) | 20.523 (0.50) |
| $5.0 \times 10^{0}$ | 47.433 (0.28) | 47.428 (0.28) | 48.215 (0.26) | 47.037 (0.26) | 45.881 (0.70) |
| $1.0 \times 10^{1}$ | 54.795 (0.24) | 54.745 (0.24) | 55.234 (0.22) | 54.368 (0.21) | 53.144 (0.59) |
| $1.5 \times 10^{1}$ | 66.101 (0.39) | 66.217 (0.39) | 66.232 (0.38) | 65.523 (0.38) | 63.791 (0.96) |
| $2.0 \times 10^{1}$ | 72.478 (0.47) | 72.595 (0.47) | 72.271 (0.46) | 71.924 (0.47) | 69.918 (1.16) |

LL = left lateral, RL = right lateral, DV = dorsal–ventral, VD = ventral–dorsal, ISO = isotropic.

### Table 5. Absorbed dose per unit neutron fluence for heart under five irradiation conditions

| Energy (MeV) | LL | RL | DV | VD | ISO |
|--------------|----|----|----|----|-----|
| $1.0 \times 10^{-9}$ | 0.475 (1.78) | 0.414 (1.85) | 0.653 (1.40) | 1.095 (1.17) | 0.509 (3.59) |
| $1.0 \times 10^{-8}$ | 0.576 (1.67) | 0.511 (1.70) | 0.777 (1.33) | 1.254 (1.21) | 0.581 (3.25) |
| $1.0 \times 10^{-7}$ | 0.680 (1.69) | 0.637 (1.83) | 0.883 (1.46) | 1.112 (1.37) | 0.698 (4.30) |
| $1.0 \times 10^{-6}$ | 0.620 (1.85) | 0.590 (1.84) | 0.736 (1.69) | 0.847 (1.61) | 0.573 (4.14) |
| $1.0 \times 10^{-5}$ | 0.552 (2.08) | 0.526 (2.02) | 0.650 (1.91) | 0.729 (1.79) | 0.498 (4.69) |
| $1.0 \times 10^{-4}$ | 0.497 (2.20) | 0.481 (2.15) | 0.580 (1.99) | 0.649 (1.85) | 0.485 (5.60) |
| $1.0 \times 10^{-3}$ | 0.505 (1.97) | 0.474 (1.86) | 0.575 (1.79) | 0.663 (1.59) | 0.456 (4.73) |
| $1.0 \times 10^{-2}$ | 0.682 (1.18) | 0.656 (1.12) | 0.729 (1.03) | 0.960 (0.79) | 0.606 (2.94) |
| $1.0 \times 10^{-1}$ | 4.597 (0.30) | 4.501 (0.30) | 4.771 (0.26) | 5.960 (0.24) | 4.090 (0.72) |
| $5.0 \times 10^{-1}$ | 13.919 (0.27) | 13.843 (0.27) | 14.309 (0.23) | 15.807 (0.22) | 12.883 (0.67) |
| $1.0 \times 10^{0}$ | 20.458 (0.27) | 20.407 (0.27) | 20.862 (0.23) | 22.363 (0.23) | 19.226 (0.66) |
| $5.0 \times 10^{0}$ | 45.749 (0.42) | 45.659 (0.41) | 45.735 (0.39) | 46.960 (0.38) | 43.758 (1.02) |
| $1.0 \times 10^{1}$ | 52.449 (0.34) | 52.355 (0.33) | 52.681 (0.32) | 53.707 (0.31) | 51.615 (0.85) |
| $1.5 \times 10^{1}$ | 63.578 (0.58) | 63.227 (0.57) | 64.166 (0.58) | 64.829 (0.56) | 63.097 (1.45) |
| $2.0 \times 10^{1}$ | 70.166 (0.73) | 69.833 (0.73) | 70.304 (0.71) | 71.246 (0.71) | 70.195 (1.86) |

LL = left lateral, RL = right lateral, DV = dorsal–ventral, VD = ventral–dorsal, ISO = isotropic.
DISCUSSION

Figures 4–6 show the neutron fluence-to-dose conversion coefficients as a function of the neutron energy under five irradiation conditions for some organs. It was found that the neutron fluence-to-dose conversion coefficients exhibited similar energy dependence for stomach, spleen, kidneys, liver, testis and bladder. Generally, for neutron energies <0.01 MeV, the conversion coefficients were ~1.0 and changed gradually with increasing neutron energy, whereas for neutron energies >0.01 MeV, the conversion coefficients increased steeply from around 1.0 to 70.0. This was mainly related to the change in neutron energy, which resulted in a change in energy deposition in the mouse body.

The organ dose conversion coefficients for some organs exhibited clear differences in the lower neutron energy range (<1 MeV) among irradiation geometries, mainly because of asymmetry in the location and orientation of organs. The difference started to disappear with neutron energies >1 MeV. For stomach and spleen, as shown in Fig. 4, the RL irradiation yielded a lower absorbed dose per unit neutron fluence compared with other irradiation geometries when the neutron energy was <1 MeV. Meanwhile, in the neutron energy range from 1 MeV to 20 MeV, we found that there was almost no difference in organ dose between the irradiation geometries. This mainly resulted from the position of the stomach and spleen, which are closer to left side of the mouse body, and the change in neutron penetrability, which correspondingly resulted in the change in energy deposition. For example, the organ dose to the stomach at 0.01 MeV and 0.1 MeV under LL irradiation conditions were, respectively, 53% and 49% lower compared with that under RL irradiation conditions. For the same reason, the organ dose conversion coefficients for the pancreas also showed similar behavior in different irradiation geometries compared with those of the spleen and stomach. For those organs that are located toward the back of the mouse (e.g. brain, kidneys and adrenal glands), the organ doses under DV irradiation conditions were higher than those under VD irradiation conditions when neutron energy was <1 MeV. Similarly, the conversion coefficients for bladder, testis, liver and heart showed reverse sensitivity to the DV and VD irradiation conditions for neutron energy <1 MeV because their positions are closer to the abdomen surface. For the organ dose conversion coefficients of the whole body skin, the minor differences between the LL and RL irradiation conditions were mainly due to the asymmetry of skin distribution in the left and right side of the mouse body, e.g. the position of feet.

Fig. 4. Neutron fluence-to-dose conversion coefficients for stomach and spleen under five irradiation conditions.

Fig. 5. Neutron fluence-to-dose conversion coefficients for kidneys and liver under five irradiation conditions.
CONCLUSION

Neutron fluence-to-dose conversion coefficients have been calculated based on the developed mouse model in the energy range of 10^{-9} to 20 MeV under five ideal irradiation geometries. The results showed that the dose conversion coefficients for all mouse organs exhibited similar energy dependence under the various ideal irradiation geometries. The results also indicated that the organ dose was sensitive to the irradiation geometries for those organs that have asymmetrical location and orientation when the neutron energy was approximately <1 MeV. The new set of conversion coefficients supplemented the mouse dosimetry and can support neutron dose–effect relation research based on mouse experiments. Since the voxel mouse model used in this work was from a normal 28-g male mouse, the organ dose conversion coefficients based on the model may not be applicable to mice actually used in experiments due to individual differences. One feasible solution to that problem is to present sets of conversion coefficients based on different weights and strains of mouse model.

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