Paper

DETERMINATION OF WHOLE-BODY AND LENS DOSE CONVERSION FACTORS FOR JAPANESE FIELD MICE, *APODEMUS SPECIOSUS*

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Abstract—**The 11 March 2011 Fukushima nuclear accident in Japan resulted in widespread radioactive contamination within the 20 km evacuation zone. Japanese field mice (*Apodemus speciosus*) living within the contaminated region received radiation doses from external environmental contamination as well as internally deposited radionuclides. Cataract formation in the lens of eyes of these mice is a possible deterministic effect of ionizing radiation; however, determination of actual doses is difficult. Since no dose conversion factors currently exist for the lens of the eyes of Japanese field mice, lens dose conversion factors were created using a Monte Carlo N-Particle simulation and compared to the International Commission on Radiological Protection Publication 108 reference rat whole-body dose conversion factors. Monte Carlo N-Particle simulations included doses to the lens of the eyes from external sources (received while both above and below ground), as well as doses from internal contamination. Although the Publication 108 reference rat is almost twice the average mass of the Japanese field mouse, all dose conversion factor calculations using Monte Carlo N-Particle methods were within approximately 37% of the Publication 108 values for the reference rat.**
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Key words: environmental assessment; environmental impact; modeling, environmental; dose, environmental

INTRODUCTION

THE NATION of Japan was struck with a disastrous earthquake and tsunami on 11 March 2011. The Fukushima Daiichi power facility had six reactor units that were directly affected by the earthquake and subsequent tsunami. Releases from the reactors included 12 PBq of ^{137}Cs and 11.8 PBq of ^{134}Cs. The total release of radioactive strontium was approximately an order of magnitude less than radiocesium due to the maximum temperatures reached by the fuel during the accident (Steinhauser et al. 2014). The resultant nearby long-term contamination provides the opportunity to study the effects of long-term low-dose irradiation of wildlife. Specifically, the formation of cataracts in the Japanese field mouse was hypothesized to be a good sentinel animal marker for predicting effects of long-term low-dose radiation.

The carcinogenic and mutagenic effects of radiation exposure are stochastic, in that the incidence (rather than the severity) of effects depends on dose. Cataract formation, however, is a nonstochastic, deterministic effect. Loss of opacity to the lens in the form of a cataract results from accumulated radiation damage. Cataracts exhibit a dose-response relationship in which the severity (rather than the incidence) is determined by the total accumulated dose. Mice living in contaminated soil are at risk of radiation-induced cataracts due to their close proximity to radionuclides in underground burrows. A correlation between the deterministic effect of cataracts and dose is being explored in a future study, necessitating a means of estimating the dose to the lens of the mouse as accurately as possible. Only the dose contributions of ^{134}Cs and ^{137}Cs were considered relevant for determining the dose to the mouse eye and whole body due to the low concentrations of other nuclides.

The International Commission on Radiation Protection (ICRP 2008a) established basic assumptions and dose conversion factors for a limited set of reference animals and plants (RAPs). Reference rat, a mouse/rat species average, was selected by ICRP to represent a small mammal based on its ubiquitous presence in most environments. Methods for determining whole-body dose to reference rat are provided by ICRP, but no methodology for organ (lens of eye) dose or smaller-mass mice is provided. While whole-body dose could provide a reasonable, first-order approximation for lens of the eye dose, a verification of this simplifying assumption was desired. The Japanese field mouse was modeled using Monte Carlo N-Particle (MCNP) and lens-specific dose conversion factors (DCFs) that were developed.

MATERIALS AND METHODS

The four rat/mouse exposure scenarios contain modeling assumptions and further descriptions:

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- External exposure, planar source: this source is an infinite planar source located below the rat and buried at a soil depth of 0.5 g cm^{-2} to simulate surface roughness.
- External exposure, volumetric source: this source is located below the rat, 10 cm thick with contamination uniformly distributed throughout, and infinite in the other two dimensions.
- External exposure, in soil (underground): this source considers the rat buried in the center of a soil column 50 cm thick and infinite in the other two dimensions. Contamination is uniformly distributed throughout the soil.
- Internal exposure: ICRP 108 (2008b) is not explicit whether the DCF concentrations are per mass of rat or per mass of the soil concentration in which the rat lives.

Whole-body dose

ICRP 108 (2008b) gives four DCF exposure scenarios (Table 1) for reference rat, two of which are the same exposure but with different source geometries: planar vs. volume.

MCNP modeling

MCNP6 and MCNPX (Werner 2017) were used throughout this research to simulate radiation sources, geometry layouts, and the absorbed dose in the target. MCNP F6 cell tallies were used to determine absorbed dose. Particle counts of 100 million provided uncertainties ranging from <0.01% to 0.6% for gamma models and <0.01% to 2% for beta models. All models were contained within a spherical universe with a 2.2 m radius. The sphere was filled with an air material (McConn et al. 2011). The area outside the sphere was given an importance of zero; particles entering this dead zone were not further considered in the simulation.

A beta particle version of each model scenario was created to test the contribution of beta radiation to whole-body dose. Since beta particles are polyenergetic and are emitted according to a spectrum, a division of energies into discreet bins was required. These energy bins, obtained from ICRP 107 (2008a), were organized into MCNP energy distribution cards for each radionuclide. The hypothesis was that the whole-body dose contribution from internally emitted beta particles would be significant, while externally emitted beta particles would prove inconsequential. ICRP 108 states that for the external models, only the dose contribution from photons was considered (ICRP 2008b).

Reproduction of ICRP 108 rat doses using MCNP. The original geometry and dose scenario assumptions from ICRP 108 were reproduced to verify the MCNP methodology for calculating mouse doses. Reference rat was modeled as a 20 cm × 6 cm × 5 cm ellipsoid with a mass of 0.314 kg (ICRP 2008b) and the Japanese field mouse was modeled as a 10 cm × 3 cm × 2.5 cm ellipsoid with a mass of 0.0393 kg (range is 20 to 60 g; Ohdachi et al. 2009). A four-component ICRU (1989) soft tissue material was chosen as the fill material for the mouse and rat ellipsoids, in accordance with ICRP 108 (2008b) assumptions.

External exposure in soil (underground)

The rat was modeled in the center of a 50-cm-thick column of radiocesium-contaminated soil (ANSI/ANS 2015), with a second uncontaminated 50-cm-thick soil cylinder below to account for any potential backscatter effects. Three different soil compositions were used to determine the effect on dose. Three soil densities ranging from 1.52 to 1.7 g cm^{-3} (McConn et al. 2011) were modeled. A minimum 0.5 m radius was used to approximate the infinite dimensions for a box surrounding a volume of soil with the rat body ellipsoid in the center, with a maximum extent of 25 cm above and 25 cm below the source. The volume of soil, minus the space and mass of the rat, was used to normalize the source activity to 1 Bq kg^{-1} soil. Five variations of the rat location in a burrow were modeled, since the ICRP does not provide burrow modeling details:

- No airspace.

Table 1. Soil density effect on dose conversion factors for the rat (DCFs are given for a 24 h time period).

Model scenario		Units	Earth	Soil	Ground	MCNP		
Soil density	Isotope	g cm^{-3}	1.52	1.6	1.7	Average	ICRP 108	%Δ[b]
External planer (surface)	^{134}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	9.3×10^{-5}	9.2×10^{-5}	9.3×10^{-5}	9.3×10^{-5}	1.2×10^{-4}	25.8
External planer (surface)	^{137}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	3.4×10^{-5}	3.4×10^{-5}	3.4×10^{-5}	3.4×10^{-5}	4.5×10^{-5}	28.1
External volumetric[a]	^{134}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	5.5×10^{-3}	5.6×10^{-3}	5.8×10^{-3}	5.7×10^{-3}	7.4×10^{-3}	26.8
External volumetric[a]	^{137}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	2.0×10^{-3}	2.0×10^{-3}	2.1×10^{-3}	2.1×10^{-3}	2.7×10^{-3}	27.7
External subterranean[a]	^{134}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	1.7×10^{-2}	1.7×10^{-2}	1.7×10^{-2}	1.7×10^{-2}	1.9×10^{-2}	11.0
External subterranean[a]	^{137}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	6.0×10^{-3}	6.1×10^{-3}	6.4×10^{-3}	6.2×10^{-3}	6.8×10^{-3}	9.7
Internal dose	^{134}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	3.9×10^{-3}	3.9×10^{-3}	3.9×10^{-3}	3.9×10^{-3}	4.1×10^{-3}	4.5
Internal dose	^{137}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	3.3×10^{-3}	3.3×10^{-3}	3.3×10^{-3}	3.3×10^{-3}	4.1×10^{-3}	21.1

[a]Assumes uniform soil distribution of activity.

[b]%Δ indicates the percent difference of ICRP 108 values and the MCNP calculated values of the DCF.

- A small, ellipsoid-shaped burrow with the rat's body centered in it.
- A small, ellipsoid-shaped burrow with the rat's body placed at the bottom.
- A larger, ellipsoid-shaped burrow with the rat centered.
- A larger, ellipsoid-shaped burrow with the rat at the bottom.

Early model trial runs showed the space surrounding the rat to be inconsequential, and thus the no-air-space scenario was used to reproduce ICRP results.

External exposure aboveground. An infinite ground source was approximated as uniformly distributed radiocesium in the top 10 cm of a 50-cm-thick cylindrical soil layer, with a 2 m radius. In all aboveground models, the ellipsoid body was placed 1.0 mm above the soil/ground layer to avoid tangential problems between the cells and surfaces. Three soil densities ranging from 1.52 to 1.7 g cm^{-3} (McConn et al. 2011) were modeled.

Internal exposure. Radiocesium was assumed to be evenly distributed throughout the ellipsoid with the origin of particles having equal probability throughout. The measured radiocesium activity was assumed to be uniformly distributed internal contamination, rather than surface skin and hair contamination.

Lens of eye dose model. Since reference rat is not an actual species, but rather a rat/mouse hybrid, no actual eye dimensions exist in ICRP 108 (2008b). The lens of the eye was modeled as a sphere of 0.2 cm radius for the rat, and 0.1 cm for the Japanese field mouse, with the exterior of the rat and mouse eye modeled as 0.22 cm and 0.11 cm radius spheres, respectively. The lens was modeled occupying 75% of the eye, and the remainder was considered as aqueous/vitreous humor. The ICRP (1975) human eye lens density of 1.1 g cm^{-3} was used, and the aqueous humor was modeled as liquid water, with a density of 1.0 g cm^{-3}.

Two eyes were placed toward the front and top of the ellipsoid with slightly more than 50% of the total eye emerging from the mouse body. The dose contribution from any cesium distributed within the eye lens or aqueous humor tissue was negligible. Use of two eyes allowed observation of consistent results and enabled averaging into a single DCF with reduced uncertainty. Due to the smaller size of the tally cell volume, a 1 billion particle count was required to produce statistics similar to the whole-body models. The source radius for the planar and volumetric source was also reduced to 0.5 m to improve the statistics resulting from a 1 billion particle run. Increasing the particle count beyond 2 billion is impractical, as it is the upper limit of available random numbers in MCNP.

RESULTS

MCNP modeling

Changing soil density had little effect on the results of the MCNP DCFs. Increasing soil density resulted in 0.1% and 5% difference in results, with dose increasing slightly with increased density (Table 1). The results of the MCNP model were compared to the ICRP 108 DCFs to verify the MCNP model. Values for ICRP 108 compared favorably with the MCNP model, with the MCNP model always producing a smaller value for the DCF. The MCNP modeled DCF was 4.5% to 28.1% lower than the ICRP 108 DCF (ICRP 2008b). The effect of burrow airspace, size, and placement of burrow within soil was also examined, but the effects were found to be negligible.

Over time, the distribution of cesium will approach an exponential distribution to a depth of approximately 10 cm, depending on the soil type and depth distribution coefficient (k_r) (NCRP 2007). The impact of an exponential distribution of both ^{134}Cs and ^{137}Cs on external volumetric dose was superficially examined. An increase in the external volumetric DCF by an average factor of 1.3, 1.6, and 1.8, with depth distribution coefficients 0.186 cm^{-1}, 0.382 cm^{-1}, and 0.566 cm^{-1}, respectively, was found. Changes due to external subterranean dose from cesium exponential decrease with depth were not examined.

The ICRP 108 DCFs were next compared to the MCNP DCF values for the mouse. Although the mouse was significantly smaller in mass than reference rat, the MCNP DCF results were similar for the rat and mouse. Comparing the mouse-specific DCFs to the ICRP 108 DCFs, the MCNP model values were always smaller, from 19% to 31.4% (Table 2).

Finally, the ICRP 108 DCFs were compared to those calculated for the lens of the eye for both the rat and mouse (ICRP 2008b). Again, the MCNP model DCFs were all less than the ICRP 108 values, with a maximum difference of 36.7% (Table 3).

DISCUSSION

The MCNP DCFs were consistently lower than the ICRP 108 values (ICRP 2008b). In most cases, the MCNP DCFs were roughly 30% below the ICRP 108 values, for almost every scenario. Varying the density of the soil and the size of the burrow in the MCNP model produced negligible changes to the MCNP DCFs.

The choice of soil material had minimal impact on dose. In calculating the average of three different soils, a weighted mean was used, which considers the individual uncertainty (weight) of each model result. This was likely unnecessary as the model output uncertainties were so close that a simple mean would have sufficed.

Table 2. Comparison of ICRP 108 dose conversion factors to MCNP whole-body dose model (DCFs are given for a 24 h time period).

Model scenario	Isotope	Units	MCNP mouse	MCNP rat	ICRP 108	%Δ ICRP and mouse
External planer (surface)	^{134}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	9.0×10^{-5}	9.3×10^{-5}	1.2×10^{-4}	29.0
External planer (surface)	^{137}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	3.3×10^{-5}	3.4×10^{-5}	4.5×10^{-5}	30.1
External volumetric[a]	^{134}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	6.0×10^{-3}	5.7×10^{-3}	7.4×10^{-3}	21.0
External volumetric[a]	^{137}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	2.1×10^{-3}	2.1×10^{-3}	2.7×10^{-3}	23.8
External subterranean[a]	^{134}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	1.6×10^{-2}	1.7×10^{-2}	1.9×10^{-2}	19.7
External subterranean[a]	^{137}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	5.6×10^{-3}	6.2×10^{-3}	6.8×10^{-3}	19.0
Internal dose	^{134}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	3.1×10^{-3}	3.9×10^{-3}	4.1×10^{-3}	28.5
Internal dose	^{137}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	3.0×10^{-3}	3.3×10^{-3}	4.1×10^{-3}	31.4

[a]Assumes uniform soil distribution of activity. An average of the three different-density soils were used to compute the conversion factors for the rat used in the above table.

The external beta dose rates were 2 orders of magnitude below the gamma results without considering range effects in the hair and skin of the mice. Only gamma dose was considered in the external models. Beta dose did not have a meaningful impact on the total dose and was not considered in further external dose models. This validated ICRP's decision to only use dose deposited from photons in the external dose scenarios.

Planar and volumetric models of soil contamination for external dose were reasonably close to ICRP values for each radionuclide and both the rat and mouse models. The external planar MCNP models, using a soil contamination depth of 0.5 g cm^{-2}, output null results only. When the contamination depth was considered at 0.0 g cm^{-2}, an external whole-body dose result on the order of the gamma results was produced. The ICRP 108 assumption accounts for surface roughness and leaf litter that may be found in a grass or forest environment or at some time after the contamination event, as a soil contamination depth of 0.5 g cm^{-2}. If the contamination was laid down freshly, on a smooth surface, whole-body dose rate effects from beta radiation may need consideration.

In all MCNP external models, the external gamma dose rate dropped with the smaller body size of the mouse vs. the rat. The exception to this, however, was the external volumetric model. The mouse received less dose from the contamination distributed in the soil, possibly due to Compton-scattered photons and to the mouse's body center of mass being closer to the surface than that of the rat. This effect, however, was not observed in the planar model, where the rat/mouse difference was less than 2%. The planar model likely produced a more uniform field due to fewer scattered photons.

The effect of burrow airspace, burrow size, and reference mouse/rat placement within the burrow was tested. A slight decrease in the range of values with increasing burrow size was noted, but in general this effect is fairly negligible. Underground MCNP models were consistent, and differed from the ICRP results by −11% and 9.7%. Due to the highly variable shapes and sizes of individual burrows and to the likely difficulty in modeling a species-specific burrow geometry, ignoring burrow airspace was validated as an ICRP 108 assumption.

Rat vs. mouse differences varied most with internal gamma dose (65% difference for both radionuclides) due to the smaller absorbed fraction in the smaller mouse bodies. Internal beta dose, however, varied the least (1.3% difference for both radionuclides). For the internal dose model, the beta radiation delivered 58% of the dose for ^{134}Cs and 82% of the dose for ^{137}Cs.

The whole-body ICRP 108 DCFs provided a reasonable estimate of dose rate to the lens of the eyes, ranging from +5.1% to +32% of the MCNP lens of eye model. In general, differences in the eye dimensions chosen had very

Table 3. Comparison of ICRP 108 dose conversion factors to MCNP lens of eye model.

Model scenario	Isotope	Units	MCNP mouse lens	MCNP rat lens	ICRP 108	%Δ ICRP and mouse
External planer (surface)	^{134}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	7.2×10^{-5}	7.2×10^{-5}	1.2×10^{-4}	33.3
External planer (surface)	^{137}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	2.7×10^{-5}	2.7×10^{-5}	4.5×10^{-5}	36.4
External volumetric[a]	^{134}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	5.0×10^{-3}	4.9×10^{-3}	7.4×10^{-3}	23.3
External volumetric[a]	^{137}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	1.8×10^{-3}	1.8×10^{-3}	2.7×10^{-3}	28.6
External subterranean[a]	^{134}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	1.8×10^{-2}	1.8×10^{-2}	1.9×10^{-2}	18.8
External subterranean[a]	^{137}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	6.4×10^{-3}	6.3×10^{-3}	6.8×10^{-3}	21.4
Internal dose	^{134}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	1.3×10^{-3}	1.0×10^{-3}	4.1×10^{-3}	32.3
Internal dose	^{137}Cs	μGy kg^{-1} Bq^{-1} d^{-1}	7.3×10^{-4}	4.9×10^{-4}	4.1×10^{-3}	36.7

[a]Assumes uniform soil distribution of activity. An average of the three different-density soils were used to compute the conversion factors for the rat used in the above table.

little impact on external dose models. It was assumed that there was negligible radiocesium deposited in the eye, and radiocesium was only present in the body of the animal. The smaller mouse eyes had a smaller aqueous humor thickness, and more beta particles penetrated to the depth of the lens. Thus, the MCNP lens model was highly dependent on the radiocesium distribution assumptions and the thickness of the aqueous humor.

CONCLUSION

A reasonable reproduction of the ICRP 108 DCF values was achieved using MCNP modeling (ICRP 2008b). The ICRP assumptions do not include dose contributions from beta particles in the external models, and the decision to neglect burrow details was validated.

In general, the ICRP whole-body dose rate conversion factors provided a good approximation of dose rates to the lens of the eye to the mouse and rat, within 37% for both species. Overall, estimation of the age of the rat or mouse and contamination levels in the areas inhabited by the mice most likely have more variability than the difference between the MCNP DCFs and the ICRP 108 DCFs.

Another important simplifying assumption was that the contamination was uniformly distributed on the surface of the ground and was uniformly distributed with depth. Future studies should explore the impact of depth distribution of contamination more fully, especially the impact on external subterranean dose.

The main limitation of the MCNP eye models was unknown distributions of radiocesium in eyes of animals. For developing internal dose models for dose to the lens of the eye, especially for other nuclides, better knowledge of this parameter would be needed to properly distribute the source material in the animal. The DCFs developed specifically for the lens of the eye for the Japanese field mouse, *Apodemus speciosus*, and for reference rat were found to be consistently lower than the ICRP 108 DCFs, by approximately 37%. Although the MCNP estimates of the DCFs are possibly more precise and accurate than ICRP 108 whole-body DCFs, the uncertainty associated with multiple other factors in estimating the dose to rats and mice are thought to be significantly higher. Thus, the use of ICRP 108 DCFs to estimate the dose to the lens of the eye is justified, as uncertainty from other factors is considered more significant.

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REFERENCES

American National Standards Institute/American Nuclear Society. Calculation and measurement of direct and scattered gamma radiation from LWR nuclear power plants. LaGrange Park, IL: American Nuclear Society; ANSI/ANS-6.6.1-2015;2015.

International Commission on Radiation Units and Measurements. Tissue substitutes in radiation dosimetry and measurement. ICRU Report 44. J ICRU 23:1; 1989.

International Commission on Radiological Protection. Report on the task group on reference man. Oxford: Permagon Press; ICRP Publication 23; 1975.

International Commission on Radiological Protection. Nuclear decay data for dosimetric calculations. Amsterdam: Elsevier Press; ICRP Publication 107; 2008a.

International Commission on Radiological Protection. Environmental protection—the concept and use of reference animals and plants. Amsterdam: Elsevier Press; ICRP Publication 108; 2008b.

McConn RJ Jr, Gesh CJ, Pagh RT, Rucker RA, Williams RG III. Compendium of material composition data for radiation transport modeling. Richland, WA: Pacific Northwest National Laboratory; PNNL-15870 Rev. 1; 2011.

National Council on Radiation Protection and Measurements. Cesium-137 in the environment: radioecology and approaches to assessment and management. Bethesda, MD: NCRP; Report 154; 2007.

Ohdachi SD, Ishibashi Y, Iwasa MA, Saitoh T, eds. The wild mammals of Japan. Kyoto, Japan: Shoukadoh Publishing; 2009: 169–171.

Steinhauser G, Brandl A, Johnson TE. Comparison of the Chernobyl and Fukushima nuclear accidents: a review of the environmental impacts. Science of the Total Environment. 470–471: 800–817; 2014. DOI 10.1016/j.scitotenv.2013.10.029.

Werner CJ, ed. MCNP users manual—code version 6.2. Los Alamos, NM: Los Alamos National Laboratory; Report LA-UR-17-29981; 2017.

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