MODELLING AND MONTE CARLO ORGAN DOSE CALCULATIONS FOR WORKERS WALKING ON GROUND CONTAMINATED WITH Cs-137 AND Co-60 GAMMA SOURCES

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A pair of walking phantoms was developed from deformable mesh phantoms to represent individuals walking on contaminated ground. The Monte Carlo N-particle extended version code was used to calculate organ doses from ground contamination scenarios involving parallel and isotropic planar sources of Cs-137 and Co-60 with concentrations of 30 kBq m⁻². For the parallel plane source case, the organ doses were up to 78 % greater for walking phantoms than those for the standing phantoms. The dose difference is because the widely open legs during walking provide less shielding to several organs, especially the kidneys, ovaries and liver, from parallel sources. The effective doses of the walking phantoms were on average 15 % higher than the standing phantoms. On the other hand, when isotropic planar sources were considered, no significant dose difference was observed. This study demonstrated the feasibility of using deformable phantoms to represent realistic postures for organ dose calculations in environmental dosimetry studies.

INTRODUCTION

Reconstruction of accidental radiation exposures of a worker requires the irradiation condition to be considered as accurately as possible to minimise the uncertainty in estimating organ doses. One particular challenge arises from the fact that most of the exposures involve realistic human postures that are not likely represented by an anthropomorphic phantom in a standing position with legs closed and arms on the sides of the body. Examples of such postures include a worker who walks on contaminated ground, or holds a container of highly radioactive materials while bending over his or her body. In these postures, some of the radiosensitive organs such as the gonads, kidneys, spleen and liver may be exposed to a different level of radiation when the legs are not in a closed and upright position. It is therefore of interest to investigate the effects of walking on the assessed organ doses and to potentially improve the dose calculations for situations where more accurate dosimetry is desirable. Clearly, such a study requires a new type of human phantoms that are deformable and representative of various body postures.

To date, more than 121 computational phantoms have been reported in the literature for ionising and non-ionising radiation dose calculations⁽¹⁾. The first-generation stylised phantoms were developed mostly between the 1960s and 1980s using simple quadratic equations describing anatomy references

recommended by the International Commission on Radiological Protection (ICRP)^(2–4). Since the late 1980s, a large number of tomographic or voxel phantoms gradually emerged as the dominant type of radiation dosimetry phantoms⁽⁵⁾. Derived from whole-body computed tomography and magnetic resonance imaging data of live subjects and cross-sectional colour photographs of cadavers, these voxel phantoms are anatomically realistic, but researchers later realised that it was extremely difficult to adjust the organ and body shape in these phantoms. In terms of computer graphics, both the stylised and voxel phantoms are based upon a general solid-geometry modelling method called constructive solid geometry^(6, 7). A more advanced type of geometry, boundary representation (BREP), has been demonstrated since the 2000s by several groups of researchers for simulating organ motions and for adjusting organ or body size and shape while preserving anatomical realism^(8, 9). To date, the BREP methods have not yet been used to design posture-changing phantoms for radiation dose calculations. A literature survey shows that the idea of changeable posture had been used to design phantoms of stylised and simple shapes^(10, 11).

This paper presents the development of a pair of adult male (AM) and adult female (AF) phantoms that were specifically designed to represent average walking individuals. These phantoms are coupled with mesh-based deformation and posture-changing software algorithms to automatically adjust the

position and posture. Organ and body sizes of these phantoms are compatible with the reference data recommended by the ICRP^(12–14). This paper also describes an application of these phantoms to an environmental exposure situation involving workers walking on the ground contaminated by Co-60 and Cs-137 sources. To understand the effects of walking postures, absorbed organ doses and effective doses from the walking phantoms are compared with those obtained from the stationary phantoms.

MATERIALS AND METHODS

An individual walking on contaminated ground is irradiated by radioactive sources from below. As such, the feet and the exact positions of the legs can affect the level of radiation shielding to organs such as the gonads, kidneys, liver and spleen. Phantoms with moving legs need to be simulated in the entire walking cycle.

Walking phantom 3D geometry modelling

The walking phantoms are based on a pair of stationary phantoms called RPI-AM and RPI-AF developed recently by Han and coworkers⁽¹⁵⁾. This pair of phantoms was designed using data recommended in ICRP Publications 23, 70 and 89 for reference AMs and AFs. On the basis of the triangular meshes, a specific type of the BREP geometry, these whole-body phantoms consist of more than 140 deformable organs and tissues.

In this study, the walking cycle is broken into four positions: (1) the left leg in the front and the right leg in the back with a pre-defined horizontal step size, (2) both legs in a closed and upright position, (3) the right leg in the front and the left leg in the back with a pre-defined horizontal step size, (4) both legs in a closed and upright position. The step size is defined as the distance between two feet and is assumed to be 70 cm for the male and 45 cm for the female. A constant walking pace is assumed in the modelling and the final organ doses from the entire walking cycle are represented by an average of doses from each of these four stages. In terms of phantom development, two new phantoms with the right and left legs in the maximum separation were developed to represent the Positions 1 and 3, using geometric deformation algorithms to adjust the legs and arms. The stationary RPI-AM and RPI-AF phantoms were used to represent the Positions 2 and 4.

A scalar multiplication method was developed to elastically deform the organ mesh models while maintaining both the position and reference organ volume. The deformation process was developed so that the volume change in the deformed organ mesh models were <1 % in comparison with ICRP recommended values. A commercial software package,

Rhinoceros, was also used to perform translation, rotation, scaling and fitting of organ models directly in the 3D space. Manipulation in 3D surfaces allowed for a higher degree of interactivity and efficiency than geometries involving the voxels. The Rhinoceros software offers a number of useful 3D tools for geometry manipulations such as deformation, fitting, Boolean operations, volume checking and a variety of 3D surface-rendering options. In dealing with adjacent organs of simple topology, the use of automatic Boolean operation to exclude overlapping space was helpful.

To adjust arm and leg positions while maintaining their anatomical structures, three issues were carefully considered: (1) the skeleton is defined with a large number of bones and joints; (2) the musculature consists of contractile muscles and immovable tendons; (3) the skin surfaces at the articulated body portions need to be smooth. The ray-casting method⁽¹⁶⁾ was used to detect the position of surfaces in real-time to avoid tissue collision by examining the distance between two adjacent vertices⁽¹⁷⁾. Each organ of the walking phantom was saved as a single 3D surface file (in the Wavefront file format) to create a library of organs. Figure 1 shows the male and female phantoms with the left leg and the right leg positioned in the front and back, respectively, at the maximum step size.

Voxelisation and tissue compositions

After the posture adjustments, the mesh-based walking phantoms were prepared for implementation into the Monte Carlo N-Particle eXtended version (MCNPX) code for organ dose calculations⁽¹⁸⁾. Since the current version of the MCNPX code cannot handle BREP-based geometries, the phantoms were converted into voxels. For this purpose, a mesh voxelisation software is developed using Visual C++ to generate voxel-formatted phantoms at a specified voxel size. The voxels for each organ model were assigned using the in-house program based on

Figure 1. Walking AM and AF phantoms with a step size of 70 and 45 cm.

parity-counting and ray-stabbing methods⁽¹⁹⁾. The walking male and female phantoms were voxelised at resolutions of 4.25 and 3.2 mm, respectively, to accommodate for the limitation of ~25 millions voxels in the MCNPX code. A larger volume of the geometry was required for the walking phantom's extended arms and legs. To confirm the validity of the transformed phantom, the mass and volume of each organ in the voxel domain were checked.

It is noted that, due to its small thickness, the skin cannot be represented directly with the specified voxel resolution. Instead, the skin was defined during the voxelisation process by adding a single layer of voxels around the body except for the eye lenses and eye balls, but with the density adjusted to match the skin reference masses of 3.3 and 2.3 kg for the male and female models, respectively. This configuration method was used in a previous study on the development of pregnant females⁽⁹⁾ and was shown to provide a reasonable degree of radiation attenuation by the skin. Specifically, skin densities of 0.29 and 0.30 g cm⁻³ were assigned to the male and female walking phantoms, respectively. For all other organs, the mass and density were specified according to ICRP Report 89⁽¹³⁾, and the tissue elemental compositions for each organ were defined based on reference values of the ICRP Report⁽¹⁴⁾ for the purposes of radiation transport simulations using Monte Carlo methods.

Monte Carlo dose calculation procedures

The walking and stationary RPI-AM and RPI-AF phantoms were used to calculate the average organ doses during a working cycle using the following equation:

$$D_w = \frac{D_1 + D_2 + D_3 + D_4}{4}, \quad (1)$$

where D_w is the final averaged dose from the whole walking cycle, and, as discussed previously, D_1 , D_2 and D_3 are doses from phantom Positions 1, 2 and 3, respectively.

To maximise the Monte Carlo computational efficiency, an in-house software was used to create an MCNPX input file from the finalised voxel phantom using the standard 'repeated structures' feature. This feature allowed one to define a box that holds the whole 3D-dimensional array of voxels and then to fill the phantom box with voxels of a different property (assigned to different organs). Organ-specific elemental compositions were based on reference values of the ICRP Publication 89⁽¹⁴⁾.

The MCPLIB04 cross-sectional library for the anatomic interactions based on EPDL 97 evaluation was used. Standard physics models for photon transport were employed including fluorescence, coherent

and incoherent scattering, pair production and bremsstrahlung generation⁽¹⁸⁾. Electrons were tracked with the Integrated Tiger Series energy indexing, which has been shown to provide more accurate results than the default indexing method⁽²⁰⁾. The photon and electron cut-off energies were set to 0.01 and 0.07 MeV, respectively.

Parallel planar sources of Cs-137 and Co-60 under a 2-cm layer of soil were assumed in the simulation of the contaminated ground. The gamma-ray energies, 662 keV from Cs-137, as well as 1173 keV (100 %) and 1333 keV (100 %) from Co-60 were separately simulated. The contamination concentration was assumed to be 30 kBq m⁻² to simulate the deposition of nuclear weapon testing fallout or a large spill on the ground⁽²¹⁾. In comparison, isotropic planar sources were also considered to simulate the contamination on the surface layer of the ground. The same contamination concentration was used. The dose calculation results were compared with data from Petoussi-Henss and Saito⁽²²⁾ for the reference adult computational phantoms.

For absorbed dose calculation, the energy pulse-height tally in the MCNPX code (also known as energy balance tally *F8: P, E) was divided by the organ mass. The *F8 tally result provided by MCNPX is normalised per source history. In order to determine the absolute organ dose rate, the dose per source photon in MCNPX was converted to dose per Bq. The running time on a personal computer (with 2.4 GHz processor and 3 GB RAM) is ~1 h per 10-million of primary photons.

RESULTS AND DISCUSSION

In the earlier sections, methods for various aspects of the model development and Monte Carlo application have been described. Here, key anatomical parameters of the resulting walking phantom models are summarised and data on the organ dose calculations are presented.

Organ mass comparison of walking phantoms and RPI-AM and RPI-FM phantoms

In order to ensure the fidelity of the organ deformation and voxelisation process, a critical step was carried out to check on the final mass of each organ⁽¹⁵⁾. The relative differences for all organs (except for the eye lenses) are within 1 %. Because of the small volume and voxel size restrained by MCNPX, the relative difference for the eye lenses is 10.5 %. These results indicate that the transformational algorithms were accurate for the purposes of radiation dosimetry.

Table 1. The organ and effective dose rates of walking phantoms from parallel planar source under 2 cm of soil with concentration of 30kBq m^{-2} . All numbers are in unit of nGy h^{-1} .

Organs	Cs-137		Co-60	
	Walking male phantom	Walking female phantom	Walking male phantom	Walking female phantom
Kidneys	3.066	3.468	16.332	17.468
Lungs	1.894	2.495	10.309	12.428
Oral mucosa	0.627	1.242	5.003	9.136
Red bone marrow	5.473	5.693	25.486	26.474
Adrenals	2.932	3.394	17.412	19.124
Gonads	31.961	6.869	114.833	32.585
Breast		10.570		46.982
Colon	6.169	7.096	27.589	30.152
Stomach wall	3.224	4.335	17.414	21.022
Esophagus	0.937	1.562	6.615	9.657
Liver	6.343	7.419	37.250	36.966
Thyroid	0.568	2.381	4.924	6.535
Brain	0.270	0.368	2.131	2.966
Bladder wall	31.961	6.869	114.833	32.585
Remainder	3.763	3.951	18.540	25.107
Effective dose	8.609		30.696

Figure 2. Organ dose and effective dose (ED) ratio plot of standing and walking male worker models from parallel planar source under 2 cm of soil with concentration of 30kBq m^{-2} . **Figure 3.** Organ dose and ED ratio plot of standing and walking female worker models from parallel planar source under 2 cm of soil with concentration of 30kBq m^{-2} .

Organ dose calculations

For the parallel planar source, only the area beneath the phantom is considered⁽²³⁾ and 10-million source photons were simulated. The statistical uncertainties for most organ doses are $<1\%$ ($<10\%$ for the eye lens). Absorbed dose rates for the lungs, gonads, liver, thyroid, brain and kidneys for the complete walking cycle calculated from Equation (1) are compared between the stationary RPI-AM and RPI-AF phantoms. Table 1 summarises all organ doses and the effective doses. The ratios of doses from the walking and standing phantoms have been plotted in Figures 2 and 3 to show the differences of these two postures.

The results show a pronounced dose difference to several organs between the walking and stationary phantoms. It is found that the walking postures cause several organs, such as the liver, kidneys and ovaries to receive up to 78 % more dose because the legs move forwards and backwards during walking, thus providing less shielding to these organs from the gamma rays emitted from the surface of the ground. Although it was originally expected to find a large difference in the dose to the gonads of the male phantom, the results show that the walking male phantom received a gonadal dose that is only 5.1 % greater than that from the standing phantom. A close inspection of the standing male phantom suggests that the standing phantom's legs are already

separated by a distance of 15 cm between the two feet. As a result, the walking male phantom does not reduce the shielding to the male gonad by too much.

The effective doses for all cases were calculated based on recommendations of ICRP Publication 103⁽²⁵⁾ and are also presented in Table 1. It shows that the effective dose to walking phantoms would be, on average, 19 % greater than that to standing phantoms under the same contamination situation. This level of improvement in both the organ and effective dose is probably worth the effort in certain high-exposure situations.

For the isotropic planar source, a series of simulations with $10 \times 10 \text{ m}^2$, $20 \times 20 \text{ m}^2$, $30 \times 30 \text{ m}^2$ and $40 \times 40 \text{ m}^2$ surface areas were performed to evaluate their dose effects. Two billion source photons were simulated for each case. The statistical uncertainties for most organ doses were $<1 \%$ ($<10 \%$ for the eye lens). The effective doses of phantoms using different source areas were plotted in Figure 4. A larger source area resulted in a higher effective dose. As shown in the Figure 4, the effective doses increased just $<2 \%$, when the source area increased from 900 to 1600 m^2 . In addition, the dose difference between the standing and walking phantoms was mainly caused by the source near the phantoms instead of the source far away. Therefore, a source surface area of 900 m^2 seemed to be adequate in the studies and was used for the following simulations.

The gonadal dose rates of walking and standing phantoms were found to differ by 1.2 %. Similar to the parallel source, for the organs located in the upper portion of the body such as the brain and the thyroid, the dose rates differ $<2.5 \%$. However, for the liver, kidneys and ovaries, no significant dose rate differences ($<3 \%$) were noticed as previously found in the simulations with the parallel source. The results indicate that the shielding effect does

not change much when legs move forwards and backwards during walking for the isotropic source. The differences of effective dose rates between the walking and standing phantoms were 1.7 and 0.3 % for Cs-137 and Co-60, respectively.

The result here was compared with the data from Petoussi-Henss and Saito⁽²²⁾. In their study, the source was at a depth of 0.5 g cm^{-2} in the ground. For the Co-60 source, the effective dose rate reported by Petoussi-Henss and Saito is 161.7 nGy h^{-1} , which is slightly lower than the dose rate from this study (173.3 nGy h^{-1}).

When compared with the dose results for the parallel source with the same contamination concentration and at a depth of 2 cm in the soil, it was the isotropic dose results were much higher. The key reason for the difference could be that the dose from the parallel source was contributed only by sources located directly beneath the phantom, whereas the isotropic sources are emitted at various angles.

DISCUSSION

Environmental dosimetry requires computational phantoms to realistically represent workers of different postures. It has been stated that it is possible and may be necessary for radiation protection dosimetry to consider person-specific anatomical phantoms in organ dose calculations⁽²⁴⁾. This study demonstrates that the use of a walking phantom is feasible and the uncertainty in the assessed organ doses for the walking workers can be reduced. There are other postures that are also very different from the stationary standing phantoms, such as sitting and bending over with a radioactive source beneath, or holding a radioactive container. It seems that when a very high dose level is involved, it is prudent to employ deformable phantoms such as those developed in this study to obtain more precise organ doses.

CONCLUSIONS

This paper describes a project to develop a pair of walking phantoms for environmental dose assessment. Organ doses from parallel planar sources of Cs-137 and Co-60 with a contamination concentration of 30 kBq m^{-2} show a pronounced dose difference (up to 78 %) to several organs, especially the kidneys, to receive more radiation. The effective doses of the walking phantoms are $\sim 15 \%$ greater than that of standing phantoms under the same contamination situation. The doses to the male and female phantoms' gonads changed 5 and 46 %, respectively. For the male gonads, the dose only changed slightly because the standing RPI-AM phantom has legs that are already slightly separated and the shielding effect from the legs is not significant. On the other hand, when isotropic sources

Figure 4. EDs of standing and walking phantoms using different source areas with the same contamination concentration (30 kBq m^{-2}).

were used for simulations, there is no significant dose difference noted.

The study demonstrated that deformable phantoms with realistic postures such as walking can and should be considered in organ dose calculations in certain environmental dosimetry studies where accurate data is desired.

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REFERENCES

1. Xu, X. G. *Chapter 1. Computational phantoms for radiation dosimetry: a 40-year history of evolution*. In: *Handbook of Anatomical Models for Radiation Dosimetry* (London, UK: Taylor & Francis) pp. 3–41 (2009).
2. Snyder, W.S., Ford, M.R., Warner, G.G. and Fisher, H.L. *Estimates of absorbed fractions for monoenergetic photon source uniformly distributed in various organs of a heterogeneous phantom*. Medical Internal Radiation Dose Committee (MIRD) Pamphlet No. 5, Supplement No. 3 (New York: Society of Nuclear Medicine) (1969).
3. *Specific absorbed fractions of energy at various ages from internal photon sources*. Report No. ORNL/TM-8381N1 (Oak Ridge, TN: Oak Ridge National Laboratory) (1987).
4. *Recommendations of the International Commission on Radiological Protection*. ICRP Publication 26 (Oxford: Pergamon) (1977).
5. Zaidi, H. and Xu, X. G. *Computational anthropomorphic models of the human anatomy: the path to realistic Monte Carlo modeling in radiological sciences*. *Annu. Rev. Biomed. Eng.* **9**, 1.1–1.30 (2007).
6. Leyton, M. *A Generative Theory of Shape* (London: Springer-Verlag) (2001).
7. Geant4-Team. *Geant4-a simulation toolkit*. *Nucl. Instrum. Methods Phys. Res. A* **506**, 250–303 (2003).
8. Stroud, I. *Boundary Representation Modeling Techniques* (London: Springer-Verlag) (2006).
9. Xu, X. G., Taranenko, V., Zhang, J. and Shi, C. *A boundary representation method for designing whole-body radiation dosimetry models: pregnant females at the ends of three gestational periods—RPI-P3, -P6 and -P9*. *Phys. Med. Biol.* **52**, 7023–7044 (2007).
10. *Development of PIMAL: Mathematical Phantom with Moving Arms and Legs*. Report No. ORNL/TM-2007/14 (Oak Ridge, TN: Oak Ridge National Laboratory) (2007).
11. Ulanovsky, A. V. and Eckerman, K. F. *Modifications to the ORNL phantom series in simulation of the responses of thyroid detectors*. *Radiat. Prot. Dosim.* **79**, 429–431 (1998).
12. *Report of the task group on Reference Man*. ICRP Publication 23 (Oxford: Pergamon) (1975).
13. International Commission on Radiological Protection. *Basic anatomical and physiological data for use in radiological protection: the skeleton*. ICRP Publication 70 (Oxford: Pergamon) (1995).
14. International Commission on Radiological Protection. *Basic anatomical and physiological data for use in radiological protection: reference values*. ICRP Publication 89 (Oxford: Pergamon) (2002).
15. Zhang, J., Na, Y., Caracappa, F. P. and Xu, X. G. *RPI-AM and RPI-AF, a pair of mesh-based, size-adjustable adult male and female computational phantoms using ICRP-89 parameters and their calculations for organ doses from monoenergetic photon beams*. *Phys. Med. Biol.* **54**, 5885–5908 (2009).
16. Amanatides, J. and Choi, K. R. *Tracing triangular meshes*. In: *The Eighth Western Computer Graphics Symposium*, Whistler, BC, Canada, pp. 43–52 (1997).
17. Na, Y. *Deformable Adult Human Phantoms for Radiation Protection Dosimetry: Methods for Adjusting Body and Organ Sizes to Match Population-Based Percentile Data*. Diss. Rensselaer Polytechnic Institute, New York. (2009).
18. *MCNPX User's Manual, Version 2.5.0*. Los Alamos National Laboratory. Report No. LA-UR-02–2607 (2005).
19. Nooruddin, F. and Turk, G. *Simplification and repair of polygonal models using volumetric techniques*. *IEEE Trans. Vis. Comput. Graph.* **9**, 191–205 (2003).
20. Jeraj, R., Keall, P. and Ostwald, P. *Comparison between MCNP, EGS4, and experiment for clinical electron beams*. *Phys. Med. Biol.* **44**, 705–717 (1999).
21. Shutov, V. N., Travnikova, I. G., Bruk, G. Y., Golikov, V. Y., Balonov, M. I., Howard, B. J., Brown, J., Strand, P., Kravtsova, E. M. and Gavrilov, A. P. *et al.* *Current contamination by ¹³⁷Cs and ⁹⁰Sr of the inhabited part of the Techa river basin in the Urals*. *J. Environ. Radioact.* **61**, 91–109 (2002).
22. Petoussi-Henss, N. and Saito, K. *Chapter 17. Applications to environmental exposures*. In: *Handbook of Anatomical Models for Radiation Dosimetry* (London, UK: Taylor & Francis) pp. 413–424 (2009).
23. Zhang, J., Bednarz, B. and Xu, X. G. *An investigation of voxel geometries for MCNP-based radiation dose calculations*. *Oper. Radiat. Saf.* **91**, S59–S65 (2006).
24. Xu, X. G., Stabin, M. G., Bolch, W. E. and Segars, W. P. *Chapter 30. Summary and future needs related to computational phantoms*. In: *Handbook of Anatomical Models for Radiation Dosimetry* (London, UK: Taylor & Francis) pp. 679–683 (2009).
25. International Commission on Radiological Protection. *Recommendations of the ICRP*. ICRP Publication 103 (2008).