A Pair of Mesh-Based Phantoms Representing ICRP-89 50th-Percentile Adult Males and Females for Radiation Protection Dosimetry Using Monte Carlo Simulations

by

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ABSTRACT

In modern radiation protection dosimetry, organ doses from various irradiation scenarios are assessed using Monte Carlo simulations involving whole-body computational phantoms representing the body of an average worker or patient. Since the 1960s, a large number of computational phantoms have been reported in the literatures for studies involving ionizing and non-ionizing radiations. Early stylized phantoms have poor anatomical shapes and are difficult to change the geometry. They are being replaced with those that are based on advanced geometries and medical images, thus affording more realism and flexibility in representing anatomical variations. This dissertation describes a research project to develop a pair of adult male and adult female computational phantoms that are compatible with the anatomical parameters for the 50th-percentile population from survey data. The phantoms were designed using entirely polygonal meshes — a Boundary REPresentation (BREP) geometry that allows for the ability to deform the shape and size of an organ, as well as the body posture. A set of original geometric models from the Anatomium™ 3D P1 V2.0 including 140 organs (out of 500 available organs) was adopted for our project. The organ masses were carefully adjusted to agree within 0.5% relative errors with the reference values provided in the Publication 89 of the International Commission on Radiological Protection (ICRP). The phantoms, called RPI Adult Male (RPI-AM) and Adult Female (RPI-AF), were then voxelized for the purpose of performing dose calculations using the MCNPX Monte Carlo code. To demonstrate the applicability, organ doses were calculated for six standard external photon and neutron source geometries, among which four of them are parallel beams: anterior-posterior, posterior-anterior, left lateral and right lateral; and the other two are 360° rotational and isotropic geometry. Monoenergetic photon beams between 10 keV and 10 MeV and neutron beams between 10^{-9} MeV and 10 GeV were considered. The results are tabulated as the fluence-to-organ-absorbed-dose conversion coefficients, as well as fluence-to-effective–dose conversion coefficients, commonly used for radiation protection dosimetry. In addition, conversion coefficients from this study were compared with those from the ICRP Computational Phantoms, REX and REGINA. It was found that these two sets of phantoms agree with each other for photons with energies greater than 1 MeV. For low-energy photons, organ absorbed

doses calculated for these two sets of phantoms have profound differences depending on specific anatomical features. For example, the brain doses from two types of phantoms are very similar for photons above 0.08 MeV. On the other hand, the lung dose differences in these two types of phantoms can be observed for photons below 2 MeV, especially for the lateral irradiations. These differences in the lung dose may be caused by relative positioning of the arms and lungs. The effective doses from these two types of phantoms differ by about 7% at 1 MeV, suggesting that these two types of phantoms are practically the same for the majority of the photon exposures encountered in radiation protection dosimetry. The effective doses for external neutron exposures were compared with those derived previously for the VIP-Man phantom and the results show approximately 20% differences due to the anatomical differences of these two types of phantoms based on the algorithm recommended by ICRP 60. For most of the energy range, the effective dose results of RPI adult phantoms calculated using the algorithm from ICRP 103 are about 50% of those from ICRP 60 due to significant update of neutron radiation weighting factors. The comparison with ICRP Computational Phantoms for the photon exposures demonstrates that this pair of RPI phantoms can be used as average workers or patients for radiation protection purposes. The reported photon and neutron datasets offer useful references for radiation protection dosimetry of the average adult male and female population against external photon and neutron exposures. The dissertation also discusses future research directions related to this pair of adult phantoms for radiation protection dosimetry. The significances of this doctoral research on RPI-AM and RPI-AF phantoms are: (1) there are more than 100 organs and tissues inside each of the phantoms with mass and volume data as recommended by ICRP Publications, (2) the phantoms mesh-based and, as such, they are deformable and anatomically realistic, (3) the effective dose results were calculated using the new algorithm recommended by ICRP Publication 103, and (4) multi-particle simulations have been demonstrated including organ doses for external neutrons. The technical capabilities afforded by this pair of RPI phantoms will dominate radiation protection dosimetry in the next 10-20 years leading to significantly more “personalized” radiation dose assessment of workers and patients.