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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

Juying Zhang¹, Yong Hum Na², Peter F Caracappa¹, and X George Xu^{1,2}

¹ Nuclear Engineering and Engineering Physics Program, Rensselaer Polytechnic Institute, Troy, NY 12180, USA

² Biomedical Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180, USA

Abstract

This paper describes the development of a pair of adult male and adult female computational phantoms that are compatible with anatomical parameters for the 50th percentile population as specified by the International Commission on Radiological Protection (ICRP). The phantoms were designed entirely using polygonal mesh surfaces—a Boundary REPresentation (BREP) geometry that affords the ability to efficiently deform the shape and size of individual organs, as well as the body posture. A set of surface mesh models, from Anatomium™ 3D P1 V2.0, including 140 organs (out of 500 available) was adopted to supply the basic anatomical representation at the organ level. The organ masses were carefully adjusted to agree within 0.5% relative error with the reference values provided in the ICRP Publication 89. The finalized phantoms have been designated the RPI adult male (RPI-AM) and adult female (RPI-AF) phantoms. For the purposes of organ dose calculations using the MCNPX Monte Carlo code, these phantoms were subsequently converted to voxel formats. Monoenergetic photons between 10 keV and 10 MeV in six standard external photon source geometries were considered in this study: four parallel beams (anterior–posterior, posterior–anterior, left lateral and right lateral), one rotational and one isotropic. The results are tabulated as fluence-to-organ-absorbed-dose conversion coefficients and fluence-to-effective-dose conversion coefficients and compared against those derived from the ICRP computational phantoms, REX and REGINA. A general agreement was found for the effective dose from these two sets of phantoms for photon energies greater than about 300 keV. However, for low-energy photons and certain individual organs, the absorbed doses exhibit profound differences due to specific anatomical features. For example, the position of the arms affects the dose to the lung by more than 20% below 300 keV in the lateral source directions, and the vertical position of the testes affects the dose by more than 80% below 150 keV in the PA source direction. The deformability and adjustability of organs and posture in the RPI adult phantoms may prove useful not only for average workers or patients for radiation protection purposes, but also in studies involving anatomical and posture variability that is important in future radiation protection dosimetry.

1. Introduction

For radiation protection and risk assessment of occupational and medical exposures, the estimate of organ doses is essential. Whole-body computational phantoms, coupled with Monte Carlo methods, have become one of the most common research tools for radiation protection dosimetry. Since the 1960s, a large number of phantoms have been reported in the literature for studies involving both ionizing and non-ionizing radiation (Caon 2004, Zaidi and Xu 2007, Eckerman *et al* 2009, Xu 2009). The anatomy in a computational phantom may be defined using different solid-geometry modeling techniques: quadric equations, voxels and advanced boundary representation (BREP) primitives such as B-splines, non-uniform rational B-splines (NURBS) or polygon meshes. Each of these techniques was prominent over a particular period of time of the last 40 years, as a result of the need for dosimetry applications and the available computer and medical imaging technologies. Based on an extensive review of chronological and modeling information found in the literature, Xu (2009) provided a detailed summary of three classes of computational phantoms: (1) stylized phantoms (1960s to 2000s); (2) voxel phantoms (1980s to 2000s) and (3) BREP phantoms (2000s to present).

BREP-based phantoms were not reported until the early 2000s. Segars (2001) was the first to demonstrate the feasibility of this type of advanced phantoms with the development of the 4D NURBS-based cardiac-torso (NCAT) phantom for nuclear medicine imaging using the Visible Human Project CT data set. Xu and Shi (2005) reported an effort to extend their 3D VIP-Man phantom to the simulation of respiratory motions by adopting the gated respiratory motion data of the NCAT phantom (Xu *et al* 2000). This 4D VIP-Man chest phantom was later used to study external-beam treatment planning for a lung cancer patient (Zhang *et al* 2008). Also researchers in University of Florida developed NURSE-based phantoms to study the influence of patient size on organ and effective dose conversion coefficients for cardiac catheterization (Johnson *et al* 2009). Xu *et al* (2007) applied the BREP techniques to develop a series of phantoms representing a pregnant woman and her fetus at the end of 3, 6, and 9 months of gestation. These phantoms, referred to as the RPI-pregnant females (RPI-P series), were defined using a mixture of polygonal mesh structures and voxels from separate anatomical information of a non-pregnant female, a 7 month pregnant woman CT data set and a mesh model of the fetus. The organ volumes were processed and adjusted using the mesh format (Xu *et al* 2007).

These recent studies involving the BREP-based phantoms (either NURBS or mesh surfaces) have demonstrated attractive flexibility and anatomical realism of the surface-geometry in comparison with the voxel-based phantoms reported between the 1980s and 2000s (Caon 2004, Zaidi and Xu 2007). However, a number of challenges must be addressed before the BREP-based phantoms may be widely adopted by the research community. Our previous experience in the development of RPI-P series phantoms suggests that the mesh geometry is very powerful in automatic or semi-automatic deformation of organs as well as in body posture adjustment, but a phantom that is based entirely on the mesh geometry does not exist. This paper reports our success in constructing a pair of mesh-based, size-adjustable phantoms, RPI adult male (RPI-AM) and RPI adult female (RPI-AF), which were adjusted to match the ICRP-89 50th percentile adult males and adult females. The surface modeling methods employed here allow this pair of phantoms to match any specific individual's size and posture, as necessary. This paper also describes the application of this pair of phantoms to the calculation of a set of dose conversion coefficients from monoenergetic external phantom beams between 10 keV to 10 MeV. The organ absorbed doses and the effective dose of this pair of phantoms are compared with those reported for REX and REGINA—a pair of voxel phantoms recently adopted by the ICRP (Zankl *et al* 2005, ICRP draft 2009).

2. Materials and methods

2.1. Geometry definition of RPI-AM and RPI-AF phantoms

The RPI-AM and RPI-AF phantoms have been developed using mesh surfaces—a BREP geometry. Surface meshes allowed the adjustment of the volume, mass and shape of the organs in arbitrary dimensions without having to deal with the underlining voxels, which can only be easily displaced along the directions of the cardinal axes. The RPI-AM and RPI-AF phantoms are intended to be used as deformable phantoms needed for dosimetry studies involving a varying body height/shape and posture. Ideally, a 'deformable phantom' requires two components: (1) a 'base' phantom that reflects an average or median population's anatomical parameters matching reference values defined by the ICRP and (2) a software algorithm to automatically adjust the base phantom into a different phantom with new desired anatomical parameters.

Figure 1 shows the schematic flowchart of the process of developing RPI-AM and RPI-AF phantoms. The deformation algorithms were implemented in MATLAB® 7.4 to computationally morph the original mesh-based organ files to match reference data. In this study, we adopted the mesh-based organ geometries of the Anatomium™ 3D P1 V2.0 (www.anatomium.com). This database has representations for over 500 different organs and structures, of which we utilize 140. Also, this dataset was collected from scanned data and the anatomy was resculpted by veteran modelers with the help of anatomists. An additional benefit of utilizing the Anatomium data is that the physical arrangement of organs is representative of standing individuals, and avoids the issues of gravity associated with phantoms derived from medical images of individuals almost inevitably taken in a supine position.

A mesh pre-processing procedure was developed to improve the quality of the original organ mesh files. The organs were eventually deformed to agree within 0.5% with the recommendations of ICRP-89 and ICRP-70 in terms of organ volume and mass (ICRP 1995, 2002). A collision detection algorithm was developed to avoid unwanted surface overlap between organs. The ray-casting method (Amanatides and Choi 1997) was used for detecting surface collision. A voxel structure was then superimposed on the finalized deformable whole-body mesh-based phantoms and the contents of each voxel were identified for inclusion in the Monte Carlo code.

2.1.1. Mesh preprocessing—The original purpose of the Anatomium™ dataset was for 3D visualization and it contains well-defined human anatomical structures. For mesh deformation and specification of an organ volume, however, the original mesh data had to be processed and refined. The pre-processing involves the unification of the data structures in a common mesh domain. A program was written that makes sure that each vertex or face was uniquely defined and the mesh surface was water-tight so that the organ volume could be accurately determined without degrading the original anatomical detail. This step was used to correct 'open meshes' that the deformation algorithm could not properly handle. Figure 2 compares the mesh quality of the mandible and teeth before and after the mesh pre-processing. In this example, the original mesh file for the 'mandible and teeth' has a total of 32 622 vertices among which 8.85% are found to be duplicated and a total of 61 640 faces among which 2.82% are found to be duplicated, leading to many holes and cracks as illustrated in figure 2(a). Through the mesh pre-processing, the problematic open meshes were corrected. Figure 2(b) shows the corrected meshes that yield smooth surfaces.

2.1.2. Mesh deformation and collision detection—In order to match internal organ volume to the ICRP recommended value, two possible approaches to the mesh deformation are considered: (1) displacement of each vertex point by a uniform factor in relation to the organ centroid, which keeps the overall mesh shape, but scales the volume or (2) the translation

of each vertex point along the direction of vertex normals by a unique scalar factor. In this approach, every vertex point was aligned as an origin of a single ray. Then, the distance between the origin and the reflecting point of the ray on an adjacent organ surface was calculated to determine whether the vertex could be relocated in the same direction of the ray. The unique scalar factor of each vertex was applied to relocate deforming vertex. In our applications, the latter approach was primarily used first for the deformation of the skeletal structures to obtain proper position and reference volume information, and then deforming the other organs in a priority order while checking for collisions with the skeleton and each other as described below. The priority list is headed by the internal organs of the chest and abdomen and followed by the minor organs and distributed tissues such as muscle and fat. The magnitudes of the deformation are chosen using iterative numerical analysis until an 'acceptance criterion' of 0.5% relative error between the deformed organ mesh volume and the ICRP recommended value for all organs except the lens of the eye is achieved (ICRP 1995, 2002).

During the deformation process, the proximity of mesh surfaces must be considered to avoid unwanted mesh overlaps since each mesh-based phantom contains more than 70 organs (i.e. tissues, contents) and 45 bone structures (cortical bone, spongiosa, medullary cavity). The ray-casting method described by Amanatides and Choi (1997) was used to detect the surfaces in real-time to avoid a collision by examining the distance between two adjacent vertices, as illustrated in figure 3. Two surfaces are considered to be in a collision if the distance between two vertices on each of the mesh surfaces is less than a pre-determined value, chosen to be 3 mm for this project. After a surface collision has been detected, the colliding vertex (denoted as a mark in figure 3) stops in that position and does not undergo further deformation. This process continues until the entire surface of each organ has been examined and the volume of the organ has matched with the given volume information.

2.1.3. Voxelization procedure of the mesh-based geometry to voxel phantoms

—For Monte Carlo calculations, a voxelization tool was developed in Visual C++ to convert the mesh-based geometries to voxel-formatted phantoms with a voxel resolution specified by the user. The in-house voxelization software is based on parity-counting and ray-stabbing methods for polygonal surfaces (Nooruddin and Turk 2003). The ray-stabbing method is suitable for closed meshes, but the parity-counting method was also used for certain tissues, such as blood vessels and muscles, where open meshes may exist. The voxelization algorithm was verified by the visual inspection of the geometries in a mesh and voxel format, as shown in an example for the skull in figure 4.

2.2. Monte Carlo simulation setup

In this project, the MCNPX (MCNP eXtended) code developed and maintained at Los Alamos National Laboratory was used for Monte Carlo calculations (Pelowitz 2005). MCNPX has the capability of simulating multiple types of particles (photon, electron, neutron, proton, etc) in a wide range of energies. Although the code system does not handle BREP-type geometries directly, the current version, MCNPX 2.5.0, provides standard features for defining the voxel geometry using the 'repeated structures' feature. MCNPX 2.5.0 is limited to a maximum of 25 million voxels, which restricts the resolution at which the voxelization routine could be applied. In this study, the RPI-AM and RPI-AF phantoms were converted to voxels with dimensions of 3.0 mm and 2.5 mm, respectively.

Six standard radiation source fields were considered: antero-posterior (AP), postero-anterior (PA), right lateral (RLAT), left lateral (LLAT), rotational (ROT) and isotropic (ISO) (ICRP 1996). Monoenergetic photon beams covering 23 energies from 10 keV to 10 MeV were simulated. Considering these energies for both phantoms and six irradiation geometries, a total of 276 separate Monte Carlo simulations were performed to yield a complete set of organ dose

data. Organ-specific elemental compositions were from ICRP Publication 89 (ICRP 2002), ICRP draft (ICRP draft 2009) and ICRU Report 46 (ICRU 1992).

For photon simulations, the MCNPX code was specified to run in the 'photon and electron' mode (Pelowitz 2005). The MCNLIB04 cross-sectional library for the anatomic interactions based on the evaluated photon interaction data library (EPDL) 97 was used. This library provides data up to 100 GeV. For the electron transport, the standard electron library EL03, covering electron energies up to 1 GeV, was used. Since the photon energy range is 10 keV–10 MeV, the detailed interactions of photon with matter includes Compton scattering, coherent scattering, fluorescence after photoelectric absorption and pair production. An energy distribution tally (the *F8: p,e card) was used to record the energy deposited inside the organs contributed by photons and electrons in units of MeV. The simulations were performed on an eight-core Monte Carlo computer server consisting of 9 GB RAM under the Linux operating system. The average time for each Monte Carlo simulation was about 200 CPU-minutes.

2.3. Effective dose calculations

The stochastic effects of radiation on the whole body is assessed using the effective dose, E , which is based on the weighted sum of equivalent doses to selected organs or tissues that were first introduced by the ICRP in Publication 60 (ICRP 1991) and later updated in Publication 103 (ICRP 2006). The calculation is shown mathematically as

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R}, \quad (1)$$

where $D_{T,R}$ is the average absorbed dose in an organ or tissue T involving the radiation type R , w_R is the radiation weighting factor for the radiation type R and w_T (see table 1) is the tissue weighting factor for the organ or tissue T (ICRP 1991; 2006). Several additional organs were assigned specific tissue weighting factors in ICRP-103, including the brain and salivary glands that belonged to the remainder tissues in ICRP-60. Also, the prostate and the lymph nodes were added to the remainder tissues in ICRP-103.

Since the effective dose is a sex-averaged value, it is computed from the equivalent doses of the male and female phantoms according to equation (2):

$$E = \sum_T w_T \left[\frac{H_T^M + H_T^F}{2} \right] \quad (2)$$

where H_T^M is the equivalent dose of organ or tissue T in the male phantom and H_T^F is that in the female phantom (ICRP 2006).

2.3.1. Bone surface—The bone surface, which consists of an approximately 10 μm thick layer of cells on all of the cortical and trabecular bone tissues, is too thin to be defined in the RPI-AM and RPI-AF phantoms. Because the vast majority of bone surface cells are part of the trabecular bone, the absorbed dose to the spongiosa structures was used as a substitute for the dose to the bone surface (Schlatl *et al* 2007).

2.3.2. Red bone marrow—The red bone marrow (RBM) in the RPI-AM and RPI-AF phantoms was defined as one component in the bone spongiosa; the other components are yellow bone marrow and the trabecular bone. The proportion of the spongiosa that consists of RBM is different from one bone to another, and the chemical composition of the spongiosa in

each bone used in the Monte Carlo simulations is slightly different in the phantoms to reflect the different proportions of the three bone tissues. The distribution of RBM and the proportion of RBM in each bone's spongiosa were specified using recommendations of ICRP Publication 70 (ICRP 1995). Given the RBM distribution in ICRP-70, the mass of RBM in each bone is summarized in table 2.

To calculate the dose to the RBM from the dose to the bone spongiosa, we have adapted the so-called three correction factor method similar to the way it was applied by Lee *et al* (2006), except that our method includes the physical properties of the spongiosa mixture rather than a whole bone homogenous mixture. Substituting the spongiosa for the homogenous whole bone into the formulation used by Lee *et al*, we can find the energy deposited in RBM of a particular bone by

$$E_{\text{RBM}}(E) = E_{\text{spongiosa}}(E) \times r_{\text{RBM}} \times \frac{\frac{[\mu_{\text{en}}(E)]_{\text{RBM}}}{\rho_{\text{RBM}}}}{\frac{[\mu_{\text{en}}(E)]_{\text{spongiosa}}}{\rho_{\text{spongiosa}}}} \times S(E), \quad (3)$$

where $E_{\text{RBM}}(E)$ is the energy deposited in the RBM at photon energy of E and $E_{\text{spongiosa}}(E)$ is the energy deposited in the spongiosa at photon energy of E . The mass fraction of RBM assigned to a certain spongiosa site is given by r_{RBM} , $(\mu_{\text{en}})_{\text{RBM}}/\rho_{\text{RBM}}$ is the mass energy absorption coefficient of red bone marrow at a photon energy of E and $(\mu_{\text{en}})_{\text{spongiosa}}/\rho_{\text{spongiosa}}$ is the mass energy absorption coefficient of the spongiosa at a photon energy of E . $S(E)$ is an additional dose enhancement factor due to the greater production of secondary electrons in trabecular bone for a particular bone and photon energy as reported by King and Spiers (1985).

The RBM dose in an individual bone can be derived from the deposited energy by converting equation (3) to equation (4),

$$D_{\text{RBM}}(E) = D_{\text{spongiosa}}(E) \times \frac{\frac{[\mu_{\text{en}}(E)]_{\text{RBM}}}{\rho_{\text{RBM}}}}{\frac{[\mu_{\text{en}}(E)]_{\text{spongiosa}}}{\rho_{\text{spongiosa}}}} \times S(E), \quad (4)$$

where $D_{\text{RBM}}(E)$ is the absorbed dose to red bone marrow at photon energy of E and $D_{\text{spongiosa}}(E)$ is the absorbed dose to the spongiosa at photon energy of E .

The dose to the spongiosa can be calculated from the photon fluence by

$$D_{\text{spongiosa}}(E) = 1.602 \times 10^{-10} \times E \times \Phi(E) \times \left(\frac{[\mu_{\text{en}}(E)]_{\text{spongiosa}}}{\rho_{\text{spongiosa}}} \right), \quad (5)$$

where $\Phi(E)$ is the photon fluence at the photon energy of E . Given the material compositions recommended by ICRP publication 89, the mass absorption coefficients of spongiosa and RBM can be calculated from the mass absorption coefficients of each component element, which is provided by National Institute of Standards and Technology (NIST) (Hubbell 1994). Since all of the factors other than photon fluence (which is determined by the Monte Carlo simulation)

are constant at constant E , they can be combined into a single energy-dependent dose response function and used to find the total dose to RBM as

$$D_{\text{RBM}} = \int_{E_{\text{min}}}^{E_{\text{max}}} R_{\text{RBM}}(E) \times \Phi(E) dE, \quad (6)$$

where $\Phi(E)$ is the photon fluence at the photon energy of E and E_{min} , E_{max} are the minimum energy and maximum energy of photon, respectively, and $R_{\text{RBM}}(E)$ is the dose response function for RBM at photon energy of E described in equation (7):

$$R_{\text{RBM}}(E) = 1.602 \times 10^{-10} \times E \times \frac{[\mu_{\text{en}}(E)]_{\text{RBM}}}{\rho_{\text{RBM}}} \times S(E_{\text{ph}}). \quad (7)$$

Equation (6) is included in the MCNPX simulation through the use of the F4 fluence tally together with a set of DE/DF cards. The dose to the RBM in each bone is calculated individually, and the whole body RBM dose is calculated as an average of the individual bone RBM doses, weighted by the mass of RBM in each bone.

2.4. ICRP phantoms

The ICRP has recommended anatomical and physiological parameters that are representative of the 50th percentile of a population for estimation of radiation doses from external and internal sources of ionizing radiation (ICRP 2002). The GSF research group has developed a pair of phantoms for the ICRP by adjusting the REX and REGINA phantoms voxel by voxel to match the ICRP reference values (Becker *et al* 2007, ICRP draft 2009). Using the same reference values, the RPI-AM and RPI-AF phantoms are adjusted in the mesh data domain instead of voxels. The ICRP reference values are intended to depict the average organ volumes and masses, without specifying the organ shapes. Therefore, in principle, the RPI phantoms (and other phantoms that match these ICRP reference parameters) are also representative of the 50th percentile of the adult population. In reality, however, the shape and location of the organs differ slightly, and therefore each phantom will exhibit different dosimetric features. A comparison between these two sets of phantoms is expected to offer insight into these issues.

3. Results and discussions

3.1. The RPI-AM and AF phantoms compatible with ICRP reference parameters

A total of 70 internal organs, 45 bone components and 4 muscle structures were processed and adjusted using the automated methods described above. Some of the organs required several iterations to achieve a satisfactory result. The relative errors in the final organ masses are less than 0.5% except for the lens of the eye (reference volume of 0.182 cm³) that has a relative error of about 3%. Table 3 summarizes the masses and volumes information about the male and female phantoms, respectively. Figure 5 displays a 3D rendering of the RPI phantoms using the processed and adjusted mesh data.

3.1.1. Kerma free-in-air to organ dose conversion coefficients—Each calculated dose value was normalized by kerma free-in-air to obtain conversion coefficients. Tables 4–7 present a sample set of these conversion coefficients, covering the absorbed doses for testes, red bone marrow of adult male, breasts and ovaries of adult female. The conversion coefficients for each of the 15 specific organs included in the calculation of the effective dose under ICRP-103 recommendations, plus the dose to the remainder tissues which is the linear average of the dose to the 13 remainder organs specified by ICRP-103 are available in Zhang (2009). Typically, 10 million histories were used for the simulations in the directions AP, LLAT,

RLAT, to obtain statistical uncertainties of organ doses less than 2%, except lens of the eye (due to its very small size) for which the statistical uncertainty was less than 10%. For ISO and ROT directions, about 40 million histories were required to achieve the statistical uncertainties of 10% for the lens of the eye, and for the PA direction, 100 million histories were required.

3.2. Kerma free-in-air to effective dose conversion coefficients

The effective dose was calculated using the method described previously in equations (1) and (2). Table 8 and figure 6 present the results of the effective dose calculations for the kerma-to-effective-dose conversion coefficients. The statistical uncertainty in all values is less than 2%.

3.3. Comparison with REX and REGINA phantoms

The organ dose results obtained using the RPI-AM and RPI-AF phantoms were compared with those from ICRP adult phantoms, REX and REGINA. As expected, for low-energy photons and for certain irradiation geometries, differences in organ doses are observed. These are analyzed by examining the anatomical differences.

3.3.1. Comparison between RPI-AM and REX

Bladder: Figure 7(a) presents the relative absorbed dose to the male bladder between the two phantom sets. For photon energies below approximately 0.3 MeV, the bladder dose in RPI-AM is lower than in REX from all source directions except the PA where the bladder dose is significantly higher. Figure 8 compares cross-sectional images of the bladder in RPI-AM and REX phantoms. The bladder position in RPI-AM is comparatively closer to the posterior side of the body than that in the REX. The difference in the shape of the body around the posterior leads to more attenuation of low-energy photons in the REX phantom.

Testes: Figure 7(b) shows the relative absorbed dose to the male testes between the RPI-AM and REX. In the PA source direction, the organ dose to the testes is significantly larger in RPI-AM than in REX for low photon energy (50% difference for the 1 MeV). For other source geometries, on the other hand, the organ doses of these two phantoms agree within 4%. Figure 9 shows the testes of the REX phantom that are in a higher vertical position in the body than in the RPI-AM phantom, and is therefore surrounded by a thicker mass of tissue from the thighs and gluteus. Therefore, the attenuation in the PA direction is much greater in the REX phantom.

Liver: Figure 7(c) shows the relative absorbed dose in the male liver. In the AP and LLAT source directions at low photon energy, the liver dose in RPI-AM exceeds that for REX by 30%, while for the PA and RLAT source directions, the opposite is observed. Figure 10 shows the cross-section images of the body in RPI-AM and REX through the center of the liver. The position of the liver in RPI-AM is closer to the left and anterior surfaces of the body than in REX, leading to the observed differences in liver dose.

Lungs: Figure 7(d) summarizes the relative absorbed dose to the male lungs. For the LLAT and RLAT source directions, the dose to the lungs is larger in RPI-AM than in REX for photon energies below 1 MeV. Figure 11 shows the cross-section images of lungs in RPI-AM and REX. The position of the arms in REX results in more reduced lung dose in the lateral exposures than in RPI-AM.

3.3.2. Comparison between RPI-AF and REGINA—In this section, selected organs unique to the female phantoms are discussed.

Ovaries: Figure 7(e) summarizes the relative absorbed dose to the female ovaries. For the AP, RLAT and LLAT source directions, the RPI-AF ovary dose is higher than in REGINA, while

it is much lower for the PA direction. The ovaries in RPI-AF are closer to the anterior surface and further to the sides than in REGINA, as shown in figure 12.

Breasts: Figure 7(f) summarizes the relative absorbed dose to the female breasts. For photon energies below 0.5 MeV, the breast dose in RPI-AF is lower than that in the REGINA, due to a thicker layer of adipose tissue around the glandular breast tissue (figure 13). Also, due to the closeness of the breast tissue to the anterior surface in REGINA, high-energy photons (photon energy is above 8 MeV) in the AP direction may result in a loss of charged particle equilibrium leading to a comparatively lower dose.

3.3.3. Effective dose—The effective dose of the RPI adult phantoms was compared with that from the ICRP phantoms for six standard external photon exposure geometries with various energies, as shown in figure 14. The comparison shows that the effective dose from these two phantom sets differ by about 7% at 1 MeV and up to 40% at 0.03 MeV. As discussed earlier, the relative position of the organs is the main cause of the difference observed for the effective dose. The effective dose calculation algorithm tends to even out the organ dose differences, as expected.

4. Conclusion

The main objective of this study was to demonstrate the feasibility of using mesh-based geometries to construct whole-body computational phantoms that are computationally efficient in deformation. The project resulted in the development of RPI-AM and RPI-AF consisting of 70 internal organs and 45 bones (including cortical bone, spongiosa and medullary cavities), all carefully adjusted to match the ICRP-89 reference values for adult males and females. Mesh-based organ deformation and mesh-overlap correction methods have been systematically developed using several software algorithms. Our results suggest that the mesh-based methods are easier to implement than the voxel-based methods, especially for automated operations.

Organ densities and elemental composition information are recommended by ICRP Publications. The mesh-based phantoms were converted to voxel-formatted data for use in Monte Carlo dose calculations. A new set of conversion coefficients from kerma free-in-air to absorbed dose and kerma free-in-air to effective dose were calculated for mono-energetic external photon beams. Standard external photon irradiation geometries covering 23 energies from 10 keV to 10 MeV were studied. In terms of the effective dose, it was found that these two types of phantoms differ by less than 10% for all standard source directions for photon energies above about 300 keV, suggesting that these two types of phantoms have similar dosimetric features for the majority of the photon exposures encountered in radiation protection dosimetry. At the organ level, it was found that the organ doses for this pair of newly developed phantoms agree with those derived from the REX and REGINA for photon energies greater than about 1 MeV, which is important in health physics applications. As expected, significant differences were observed in individual organs at low photon energies where small differences in the relative organ position can result in large differences in the calculated dose.

It is important to note that this pair of phantoms was developed by mesh-based methods, which allows their shapes and sizes to be easily adjusted. Deformation of this pair of phantoms to match specific individuals (such as REX and REGINA) is now possible and will be fully demonstrated in the future. Additional possible features of these deformable phantoms include posture changes and virtual-reality-based dose simulations of realistic exposure scenarios (Ding *et al* 2009).

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Figure 1. Flowchart of the mesh-based surface modeling method used to develop the RPI-AM and RPI-AF phantoms.

Figure 2. Comparison of mesh quality with and without the mesh pre-processing of the mandible and teeth. (a) Before the pre-processing, the meshes have a lot of surface cracks. (b) The corrected meshes are closed and result in smooth surfaces.

Figure 3. Illustration of the collision detection algorithm for surfaces A and B representing two organ surfaces. A collision point between two surfaces occurs when the distance between a vertex (labeled as ⊗) and the other surface along the normal direction is less than a pre-determined value. The detection continues until all the vertices on both the surfaces have been examined this way.

Figure 4. Visual inspection of the male skull which was converted from the mesh to voxel geometry: (a) mesh format, (b) surface rendering using 3D Doctor (Able Software Corp., Lexington, MA) in the voxel format.

Figure 5.
Surface rendering of 3D phantoms: (a) RPI-AM, (b) RPI-AF.

Figure 6.
The effective dose per unit kerma free-in-air (E/K_a) calculated using the RPI adult phantoms.

Figure 7. Ratio of the organ absorbed dose of the RPI Adult phantoms to that of the ICRP phantoms: (a) male bladder; (b) male testes; (c) male liver; (d) male lung; (e) female ovary; (f) female breast.

Figure 8. Comparison of the bladder position showing the different anatomical arrangement: (a) RPI-AM phantom and (b) REX phantom.

Figure 9.
Comparison of the testis position showing the different organ location level: (a) RPI-AM phantom and (b) REX phantom.

Figure 10. Comparison of the liver position showing the different organ location: (a) RPI-AM phantom and (b) REX phantom.

Figure 11.

Comparison of the lung position showing the different anatomical medium around: (a) RPI-AM phantom and (b) REX phantom.

Figure 12.
Comparison of the ovary position: (a) RPI-AF phantom and (b) REGINA phantom.

Figure 13.
Comparison of the breast position: (a) RPI-AF phantom and (b) REGINA phantom.

Figure 14.
Ratio of the effective dose of RPI adult phantoms to that of ICRP phantoms.

Table 1

Tissue weighting factors by ICRP-60 and ICRP-103.

Tissue	w_T	
	ICRP60	ICRP103
Bonemarrow (red)	0.12	0.12
Colon	0.12	0.12
Lung	0.12	0.12
Stomach	0.12	0.12
Breast	0.05	0.12
Remainder tissues	0.05 ^a	0.12 ^b
Gonads	0.2	0.08
Bladder	0.05	0.04
Esophagus	0.05	0.04
Liver	0.05	0.04
Thyroid	0.05	0.04
Bone surface	0.01	0.01
Brain	0	0.01
Salivary glands	0	0.01
Skin	0.01	0.01

^a Remainder tissues defined in ICRP-60: adrenals, brain, upper large intestine, small intestine, kidneys, muscle, pancreas, spleen, thymus, and uterus.

^b Remainder tissues defined in ICRP-103: adrenals, extrathoracic (ET) region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, uterus/cervix.

Table 2

Red bone marrow distribution recommended by ICRP-70 (1995) and the resultant RBM mass in each bone.

Organ	Fraction of whole body RBM (%)	RBM mass (g) in bone of the male phantom	RBM mass in bone of the female phantom (g)
Cranium spongiosa	7.7	90.09	69.3
Mandible spongiosa	0.8	9.36	7.2
Scapulae spongiosa	2.9	33.93	26.1
Clavicles spongiosa	0.8	9.36	7.2
Sternum spongiosa	3	35.1	27
Rib spongiosa	15.2	177.84	136.8
Cervical Spine spongiosa	3.7	43.29	33.3
Thoracic Spine spongiosa	15.3	179.01	137.7
Lumbar Spine spongiosa	11.7	136.89	105.3
Sacrum spongiosa	9.4	109.98	84.6
Os coxae spongiosa	19.5	228.15	175.5
Femora upper spongiosa	7.4	86.58	66.6
Humeri upper spongiosa	2.5	29.25	22.5

Table 3

Organ/tissue masses, densities and volumes for the RPI-AM phantom.

Organ	RPI-AM organ or organ segment mass (g)		RPI-AF organ or organ segment mass (g)	
	RPI-AM	Reference	RPI-AF	Reference
Adrenal, left	7.02E+00	7.00E+00	6.49E+00	6.50E+00
Adrenal, right	7.00E+00	7.00E+00	6.49E+00	6.50E+00
Extrathoracic (ET)	3.94E+01	3.94E+01	1.86E+01	1.86E+01
Oral mucosa, tongue	3.07E+01	3.10E+01	9.01E+00	9.00E+00
Trachea	9.98E+00	1.00E+01	8.00E+00	8.00E+00
Bronchi	3.00E+01	3.00E+01	2.50E+01	2.50E+01
Blood vessels, head	8.60E-01	8.50E-01	6.06E+00	6.06E+00
Blood vessels, trunk	2.72E+02	2.72E+02	2.42E+02	2.42E+02
Blood vessels, arms	1.57E+01	1.57E+01	4.32E+01	4.32E+01
Blood vessels, legs	8.30E+01	8.30E+01	9.27E+01	9.26E+01
Humeri, upper half, cortical	1.36E+02	1.35E+02	1.13E+02	1.13E+02
Humeri, upper half, spongiosa	1.85E+02	1.85E+02	1.12E+02	1.12E+02
Humeri, upper half, medullary cavity	3.35E+01	3.35E+01	1.99E+01	1.99E+01
Humeri, lower half, cortical	1.28E+02	1.28E+02	1.02E+02	1.02E+02
Humeri, lower half, spongiosa	5.97E+01	5.97E+01	5.28E+01	5.28E+01
Humeri, lower half, medullary cavity	3.73E+01	3.71E+01	2.05E+01	2.06E+01
Ulnae and radii: ulnae and radii, cortical	2.71E+02	2.71E+02	1.55E+02	1.55E+02
Ulnae and radii, spongiosa	1.82E+02	1.82E+02	9.12E+01	9.12E+01
Ulnae and radii, medullary cavity	2.27E+01	2.27E+01	3.36E+01	3.36E+01
Wrists and hand bones, cortical	1.80E+02	1.80E+02	1.04E+02	1.04E+02
Wrists and hand bones, spongiosa	1.40E+02	1.40E+02	7.29E+01	7.28E+01
Clavicles, cortical	4.78E+01	4.78E+01	3.25E+01	3.25E+01
Clavicles, spongiosa	5.31E+01	5.31E+01	4.05E+01	4.05E+01
Cranium, cortical	5.63E+02	5.63E+02	4.04E+02	4.04E+02
Cranium, spongiosa	4.51E+02	4.51E+02	4.17E+02	4.17E+02
Femora, upper half, cortical	2.62E+02	2.62E+02	2.48E+02	2.48E+02
Femora, upper half, spongiosa	4.72E+02	4.72E+02	2.25E+02	2.25E+02
Femora, upper half, medullary cavity	2.58E+01	2.58E+01	3.94E+01	3.95E+01
Femora, lower half, cortical	2.94E+02	2.94E+02	2.32E+02	2.32E+02
Femora, lower half, spongiosa	4.39E+02	4.39E+02	1.74E+02	1.75E+02
Femora, lower half, medullary cavity	8.09E+01	8.09E+01	5.57E+01	5.54E+01
Tibiae, fibulae and patellae, cortical	5.31E+02	5.31E+02	6.14E+02	6.19E+02
Tibiae, fibulae and patellae, spongiosa	7.29E+02	7.29E+02	5.87E+02	5.87E+02

Organ	RPI-AM organ or organ segment mass (g)		RPI-AF organ or organ segment mass (g)	
	RPI-AM	Reference	RPI-AF	Reference
Tibiae, fibulae and patellae, medullary cavity	7.80E+01	7.87E+01	8.77E+01	8.77E+01
Ankles and foot bones, cortical	2.33E+02	2.33E+02	1.72E+02	1.72E+02
Ankles and foot bones, spongiosa	5.07E+02	5.08E+02	2.70E+02	2.70E+02
Mandible, cortical	7.61E+01	7.61E+01	4.50E+01	4.49E+01
Mandible, spongiosa	7.39E+01	7.39E+01	3.47E+01	3.47E+01
Pelvis, cortical	3.99E+02	3.99E+02	2.60E+02	2.60E+02
Pelvis, spongiosa	6.81E+02	6.81E+02	4.45E+02	4.45E+02
Ribs, cortical	3.65E+02	3.65E+02	1.63E+02	1.63E+02
Ribs, spongiosa	5.20E+02	5.20E+02	2.59E+02	2.59E+02
Scapulae, cortical	2.21E+02	2.21E+02	1.20E+02	1.20E+02
Scapulae, spongiosa	1.90E+02	1.92E+02	9.69E+01	9.69E+01
Cervical spine, cortical	1.03E+02	1.03E+02	7.09E+01	7.09E+01
Cervical spine, spongiosa	7.36E+01	7.36E+01	7.28E+01	7.28E+01
Thoracic spine, cortical	2.87E+02	2.87E+02	2.04E+02	2.04E+02
Thoracic spine, spongiosa	3.35E+02	3.35E+02	2.53E+02	2.53E+02
Lumbar spine, cortical	1.86E+02	1.86E+02	1.55E+02	1.55E+02
Lumbar spine, spongiosa	3.01E+02	3.02E+02	2.61E+02	2.61E+02
Sacrum, cortical	1.09E+02	1.09E+02	0.00E+00	0.00E+00
Sacrum, spongiosa	1.73E+02	1.74E+02	1.41E+02	1.41E+02
Sternum, cortical	9.90E+00	9.89E+00	1.68E+00	1.67E+00
Sternum, spongiosa	5.63E+01	5.63E+01	4.74E+01	4.74E+01
Cartilage	8.81E+01	8.87E+01	3.14E+02	3.14E+02
Brain	1.45E+03	1.45E+03	1.30E+03	1.30E+03
Breast, left, adipose tissue	7.49E+00	7.50E+00	1.50E+02	1.50E+02
Breast, left, glandular tissue	4.98E+00	4.99E+00	9.97E+01	1.00E+02
Breast, right, adipose tissue	7.49E+00	7.50E+00	1.50E+02	1.50E+02
Breast, right, glandular tissue	4.98E+00	4.99E+00	9.97E+01	1.00E+02
Eye lens, left	2.10E-01	2.10E-01	2.10E-01	2.10E-01
Eye bulb, left	7.29E+00	7.30E+00	7.29E+00	7.30E+00
Eye lens, right	2.10E-01	2.00E-01	2.10E-01	2.00E-01
Eye bulb, right	7.29E+00	7.30E+00	7.29E+00	7.30E+00
Gall bladder wall	1.00E+01	1.00E+01	8.01E+00	8.00E+00
Gall bladder contents	5.77E+01	5.80E+01	4.79E+01	4.80E+01
Stomach wall	1.50E+02	1.50E+02	1.40E+02	1.40E+02
Stomach contents	2.51E+02	2.50E+02	2.30E+02	2.30E+02
Small intestine	1.00E+03	1.00E+03	8.80E+02	8.80E+02
Ascending colon wall	9.00E+01	9.00E+01	9.00E+01	9.00E+01
Ascending colon contents	5.50E+01	5.50E+01	1.00E+02	1.00E+02
Transverse colon wall, right	6.00E+01	6.00E+01	5.50E+01	5.50E+01
Transverse colon contents, right	9.50E+01	9.50E+01	6.00E+01	6.00E+01

Organ	RPI-AM organ or organ segment mass (g)		RPI-AF organ or organ segment mass (g)	
	RPI-AM	Reference	RPI-AF	Reference
Transverse colon wall, left	6.00E+01	6.00E+01	5.50E+01	5.50E+01
Transverse colon contents, left	4.00E+01	4.00E+01	3.00E+01	3.00E+01
Descending colon wall	9.00E+01	9.00E+01	9.00E+01	9.00E+01
Descending colon contents	3.50E+01	3.50E+01	5.00E+01	5.00E+01
Sigmoid colon wall	4.00E+01	4.00E+01	4.50E+01	4.50E+01
Sigmoid colon contents	7.50E+01	7.50E+01	8.00E+01	8.00E+01
Rectum wall	3.01E+01	3.00E+01	2.51E+01	2.50E+01
Heart wall	3.30E+02	3.30E+02	2.50E+02	2.50E+02
Heart contents(blood)	5.10E+02	5.10E+02	3.70E+02	3.70E+02
Kidney, left, cortex	1.07E+02	1.07E+02	1.05E+02	1.05E+02
Kidney, left, medulla	3.82E+01	3.83E+01	3.74E+01	3.74E+01
Kidney, left, pelvis	7.63E+00	7.63E+00	7.46E+00	7.48E+00
Kidney, right, cortex	1.10E+02	1.10E+02	8.79E+01	8.79E+01
Kidney, right, medulla	3.92E+01	3.93E+01	3.14E+01	3.14E+01
Kidney, right, pelvis	7.85E+00	7.87E+00	6.27E+00	6.28E+00
Liver	1.80E+03	1.80E+03	1.40E+03	1.40E+03
Lung, left, tissue	5.50E+02	5.53E+02	4.22E+02	4.22E+02
Lung, right, tissue	6.43E+02	6.47E+02	5.28E+02	5.28E+02
Lymphatic nodes, extrathoracic airways	2.25E+00	2.26E+00	1.32E+00	1.34E+00
Lymphatic nodes, thoracic airways	6.40E+00	6.40E+00	3.86E+00	3.86E+00
Lymphatic nodes, head	5.98E+00	5.98E+00	2.58E+00	2.58E+00
Lymphatic nodes, trunk	1.04E+02	1.04E+02	5.77E+01	5.77E+01
Lymphatic nodes, arms	7.81E+00	7.83E+00	3.89E+00	3.90E+00
Lymphatic nodes, legs	1.11E+01	1.11E+01	9.79E+00	9.80E+00
Muscle, head	1.22E+03	1.22E+03	4.02E+02	4.02E+02
Muscle, trunk	1.50E+04	1.50E+04	8.52E+03	8.52E+03
Muscle, arms	2.75E+03	2.75E+03	1.52E+03	1.52E+03
Muscle, legs	1.00E+04	1.00E+04	7.05E+03	7.05E+03
Oesophagus	4.00E+01	4.00E+01	3.50E+01	3.50E+01
Ovary, left	7.02E+00		5.49E+00	5.50E+00
Ovary, right	7.00E+00		5.49E+00	5.50E+00
Pancreas	3.94E+01	1.40E+02	1.20E+02	1.20E+02
Pituitary gland	3.07E+01	6.00E-01	6.00E-01	6.00E-01
Prostate	9.98E+00	1.70E+01		
Residual tissue	3.00E+01			
Salivary glands, left	8.60E-01	4.25E+01	3.50E+01	3.50E+01
Salivary glands, right	2.72E+02	4.25E+01	3.50E+01	3.50E+01
Skin	1.57E+01	3.30E+03	2.30E+03	2.30E+03
Spinal cord	8.30E+01	3.00E+01	2.80E+01	2.80E+01

Organ	RPI-AM organ or organ segment mass (g)		RPI-AF organ or organ segment mass (g)	
	RPI-AM	Reference	RPI-AF	Reference
Spleen	1.36E+02	1.50E+02	1.50E+02	1.50E+02
Teeth	1.85E+02	5.00E+01	4.00E+01	4.00E+01
Testis, left	3.35E+01	1.75E+01		
Testis, right	1.28E+02	1.75E+01		
Thymus	5.97E+01	2.50E+01	2.00E+01	2.00E+01
Thyroid	3.73E+01	2.00E+01	1.71E+01	1.70E+01
Tongue (inner part)	2.71E+02	4.20E+01	5.12E+01	5.00E+01
Tonsils	1.82E+02	3.00E+00	3.00E+00	3.00E+00
Ureter, left	2.27E+01	8.50E+00	7.64E+00	7.50E+00
Ureter, right	1.80E+02	7.50E+00	7.52E+00	7.50E+00
Urinary bladder wall	1.40E+02	5.00E+01	4.00E+01	4.00E+01
Urinary bladder contents	4.78E+01	2.00E+02	2.00E+02	2.00E+02
Uterus			7.99E+01	8.00E+01
Air inside body	N/A	N/A	N/A	N/A

Table 4

The male testes absorbed dose per unit kerma free-in-air (D_T/K_d) for monoenergetic photons.

Energy (MeV)	AP	PA	LLAT	RLAT	ROT	ISO
0.010	0.000	0.000	0.000	0.000	0.000	0.000
0.015	0.018	0.014	0.000	0.002	0.006	0.005
0.020	0.136	0.108	0.000	0.000	0.045	0.041
0.030	0.646	0.437	0.026	0.024	0.235	0.208
0.040	1.181	0.744	0.131	0.125	0.486	0.424
0.050	1.574	0.976	0.258	0.257	0.706	0.626
0.060	1.746	1.147	0.376	0.387	0.807	0.723
0.080	1.793	1.211	0.477	0.468	0.893	0.795
0.100	1.707	1.218	0.495	0.482	0.861	0.775
0.150	1.476	1.182	0.483	0.471	0.801	0.709
0.200	1.366	1.147	0.477	0.475	0.764	0.681
0.300	1.254	1.126	0.509	0.497	0.745	0.663
0.400	1.205	1.138	0.529	0.525	0.722	0.664
0.500	1.180	1.146	0.552	0.560	0.735	0.664
0.600	1.146	1.154	0.570	0.572	0.753	0.681
0.800	1.099	1.162	0.770	0.617	0.770	0.698
1.000	1.099	1.144	0.632	0.652	0.762	0.701
2.000	1.041	1.160	0.732	0.732	0.786	0.757
4.000	1.034	1.146	0.793	0.794	0.851	0.814
6.000	0.982	1.085	0.830	0.827	0.889	0.852
8.000	0.921	1.041	0.857	0.846	0.869	0.820
10.000	0.867	0.971	0.850	0.834	0.873	0.813

Table 5

The male red bone marrow absorbed dose per unit kerma free-in-air (D_T/K_a) for monoenergetic photons.

Energy (MeV)	AP	PA	LLAT	RLAT	ROT	ISO
0.010	0.000	0.000	0.000	0.000	0.000	0.000
0.015	0.003	0.001	0.001	0.002	0.002	0.001
0.020	0.011	0.011	0.007	0.008	0.009	0.007
0.030	0.066	0.112	0.052	0.054	0.071	0.055
0.040	0.202	0.340	0.156	0.159	0.220	0.171
0.050	0.384	0.616	0.294	0.298	0.408	0.324
0.060	0.542	0.838	0.415	0.420	0.570	0.457
0.080	0.719	1.067	0.551	0.556	0.745	0.603
0.100	0.770	1.115	0.592	0.596	0.793	0.644
0.150	0.760	1.069	0.590	0.594	0.779	0.637
0.200	0.748	1.029	0.586	0.590	0.762	0.629
0.300	0.743	0.986	0.591	0.594	0.752	0.628
0.400	0.745	0.965	0.602	0.605	0.753	0.635
0.500	0.751	0.953	0.613	0.616	0.757	0.644
0.600	0.759	0.948	0.626	0.628	0.764	0.655
0.800	0.774	0.944	0.650	0.651	0.777	0.676
1.000	0.787	0.941	0.669	0.671	0.788	0.693
2.000	0.837	0.950	0.740	0.741	0.832	0.756
4.000	0.875	0.958	0.800	0.802	0.867	0.810
6.000	0.878	0.949	0.816	0.817	0.869	0.823
8.000	0.867	0.930	0.812	0.813	0.857	0.817
10.000	0.859	0.917	0.809	0.809	0.849	0.812

Table 6

The female breast absorbed dose per unit kerma free-in-air (D_T/K_a) for monoenergetic photons.

Energy (MeV)	AP	PA	LLAT	RLAT	ROT	ISO
0.010	0.000	0.000	0.000	0.000	0.000	0.000
0.015	0.018	0.0	0.004	0.002	0.006	0.005
0.020	0.112	0.000	0.036	0.028	0.046	0.040
0.030	0.440	0.21	0.180	0.164	0.210	0.193
0.040	0.764	0.101	0.333	0.318	0.394	0.362
0.050	1.027	0.205	0.475	0.456	0.561	0.508
0.060	1.202	0.305	0.577	0.562	0.694	0.609
0.080	1.350	0.418	0.679	0.658	0.795	0.716
0.100	1.363	0.473	0.713	0.690	0.812	0.750
0.150	1.283	0.517	0.707	0.691	0.815	0.745
0.200	1.217	0.541	0.709	0.689	0.811	0.733
0.300	1.152	0.594	0.710	0.693	0.789	0.739
0.400	1.118	0.627	0.717	0.703	0.799	0.745
0.500	1.090	0.657	0.721	0.713	0.808	0.749
0.600	1.079	0.686	0.731	0.723	0.817	0.750
0.800	1.065	0.719	0.755	0.742	0.840	0.770
1.000	1.059	0.749	0.769	0.752	0.844	0.783
2.000	1.063	0.840	0.840	0.811	0.880	0.844
4.000	1.057	0.897	0.900	0.864	0.932	0.887
6.000	1.026	0.900	0.895	0.882	0.921	0.895
8.000	0.971	0.892	0.874	0.885	0.893	0.887
10.000	0.907	0.894	0.864	0.873	0.859	0.871

Table 7

The female ovary absorbed dose per unit kerma free-in-air (D_T/K_a) for monoenergetic photons.

Energy (MeV)	AP	PA	LLAT	RLAT	ROT	ISO
0.010	0.000	0.000	0.000	0.000	0.000	0.000
0.015	0.000	0.000	0.000	0.000	0.000	0.000
0.020	0.000	0.001	0.000	0.000	0.000	0.000
0.030	0.095	0.071	0.027	0.026	0.065	0.030
0.040	0.382	0.305	0.157	0.153	0.227	0.175
0.050	0.713	0.621	0.347	0.310	0.525	0.362
0.060	1.002	0.863	0.507	0.462	0.688	0.513
0.080	1.128	1.016	0.696	0.602	0.910	0.641
0.100	1.098	1.106	0.689	0.655	0.856	0.652
0.150	1.048	1.007	0.650	0.612	0.834	0.557
0.200	0.948	0.924	0.619	0.610	0.803	0.550
0.300	0.900	0.916	0.623	0.648	0.742	0.537
0.400	0.882	0.918	0.650	0.667	0.699	0.528
0.500	0.887	0.875	0.655	0.668	0.734	0.576
0.600	0.877	0.893	0.698	0.694	0.773	0.551
0.800	0.890	0.905	0.678	0.736	0.808	0.613
1.000	0.904	0.937	0.724	0.755	0.848	0.625
2.000	0.922	0.946	0.740	0.810	0.830	0.711
4.000	0.960	0.982	0.846	0.893	0.769	0.759
6.000	0.951	0.981	0.825	0.915	0.848	0.802
8.000	0.952	0.953	0.838	0.921	0.852	0.796
10.000	0.950	1.002	0.849	0.910	0.774	0.785

Table 8

Effective dose per unit kerma free-in-air (E/K_a) using the RPI adult phantoms for monoenergetic external standard photon exposure geometries.

Energy (MeV)	AP	PA	LLAT	RLAT	ROT	ISO
0.010	0.003	0.002	0.002	0.002	0.002	0.002
0.015	0.012	0.006	0.005	0.005	0.007	0.006
0.020	0.054	0.020	0.017	0.016	0.027	0.022
0.030	0.259	0.127	0.150	0.098	0.150	0.116
0.040	0.562	0.343	0.279	0.247	0.363	0.284
0.050	0.851	0.585	0.457	0.409	0.584	0.460
0.060	1.045	0.769	0.587	0.535	0.739	0.590
0.080	1.177	0.922	0.701	0.639	0.874	0.701
0.100	1.170	0.949	0.716	0.661	0.881	0.714
0.150	1.075	0.899	0.687	0.641	0.833	0.674
0.200	1.017	0.865	0.671	0.632	0.803	0.657
0.300	0.964	0.849	0.6340	0.634	0.784	0.650
0.400	0.944	0.845	0.678	0.646	0.779	0.654
0.500	0.933	0.843	0.689	0.659	0.781	0.663
0.600	0.928	0.847	0.701	0.672	0.790	0.672
0.800	0.928	0.861	0.721	0.699	0.803	0.692
1.000	0.928	0.870	0.741	0.717	0.813	0.709
2.000	0.939	0.908	0.802	0.784	0.854	0.770
4.000	0.959	0.941	0.858	0.846	0.884	0.829
6.000	0.950	0.938	0.874	0.860	0.895	0.846
8.000	0.931	0.928	0.872	0.864	0.884	0.845
10.000	0.903	0.921	0.869	0.858	0.872	0.843