Published in final edited form as:

Phys Med Biol. 2010 July 7; 55(13): 3789–3811. doi:10.1088/0031-9155/55/13/015.

Deformable adult human phantoms for radiation protection dosimetry: anthropometric data representing size distributions of adult worker populations and software algorithms

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Abstract

Computational phantoms representing workers and patients are essential in estimating organ doses from various occupational radiation exposures and medical procedures. Nearly all existing phantoms, however, were purposely designed to match internal and external anatomical features of the Reference Man as defined by the International Commission on Radiological Protection (ICRP). To reduce uncertainty in dose calculations caused by anatomical variations, a new generation of phantoms of varying organ and body sizes is needed. This paper presents detailed anatomical data in tables and graphs that are used to design such size-adjustable phantoms representing a range of adult individuals in terms of the body height, body weight and internal organ volume/mass. Two different sets of information are used to derive the phantom sets: (1) individual internal organ size and volume/mass distribution data derived from the recommendations of the ICRP in Publications 23 and 89 and (2) whole-body height and weight percentile data from the National Health and Nutrition Examination Survey (NHANES 1999–2002). The NHANES height and weight data for 19 year old males and females are used to estimate the distributions of individuals' size, which is unknown, that corresponds to the ICRP organ and tissue distributions. This paper then demonstrates the usage of these anthropometric data in the development of deformable anatomical phantoms. A pair of phantoms—modeled entirely in mesh surfaces—of the adult male and female, RPI-adult male (AM) and RPI-adult female (AF) are used as the base for size-adjustable phantoms. To create percentile-specific phantoms from these two base phantoms, organ surface boundaries are carefully altered according to the tabulated anthropometric data. Software algorithms are developed to automatically match the organ volumes and masses with desired values. Finally, these mesh-based, percentile-specific phantoms are converted into voxel-based phantoms for Monte Carlo radiation transport simulations. This paper also compares absorbed organ doses for the RPI-AM-5th-height and -weight percentile phantom (165 cm in height and 56 kg in weight) and the RPI-AM-95th-height and -weight percentile phantom (188 cm in height and 110 kg in weight) with those for the RPI-AM-50th-height and -weight percentile phantom (176 cm in height and 73 kg in weight) from exposures to 0.5 MeV external photon beams. The results suggest a general finding that the phantoms representing a slimmer and shorter individual male received higher absorbed organ doses because of lesser degree of photon attenuation due to smaller amount of body fat. In particular, doses to the prostate and adrenal in the RPI-AM-5th-height and -weight percentile phantom is about 10% greater than those in the RPI-AM-50th-height and -weight percentile phantom approximating the ICRP Reference Man. On the other hand, the doses to the prostate and adrenal in the RPI-AM-95th-height and -weight percentile phantom are approximately 20% greater than those in the RPI-AM-50th-height and -weight percentile phantom. Although this study only considered the photon radiation of limited energies and irradiation geometries, the

potential to improve the organ dose accuracy using the deformable phantom technology is clearly demonstrated.

1. Introduction

Computational phantoms of the human body serve as a powerful tool to many radiation protection dosimetry studies involving both occupational and medical exposures. In the past 40 years, more than 100 phantoms—spanning three generations with distinctive features—have been reported and applied to both ionizing and non-ionizing radiation studies (Xu 2009). The first-generation of computational phantoms were designed to mimic the anatomy through the use of three-dimensional surface equations (Snyder *et al* 1978). These phantoms were later revised to yield a family of phantoms of both genders and different ages (Cristy and Eckerman 1987). To remedy the lack of anatomical realism and detail in these stylized phantoms, the use of second-generation voxel phantoms has mushroomed since the 1980s (Petoussi-Henss *et al* 2002, Caon 2004, Zaidi and Xu 2007, Xu 2009). Voxel phantoms were constructed based on tomographic images acquired by computed tomography (CT) or magnetic resonance imaging (MRI) of patients, as well as high-resolution anatomical imaging of cadavers such as those from the Visible Human Project in the USA and China (Xu 2009, Eckerman *et al* 2009). A voxel phantom provides an anatomically true representation of the subject who often differs from the average individual. Since the format of the voxels is not convenient for geometric modifications, a relatively new and novel computer graphics method has been adopted to create the third-generation phantoms using the boundary representation (BREP) technologies (Xu 2009). BREP phantoms appear in the form of non-uniform rational b-splines (NURBS) or polygon mesh surfaces. BREP phantoms have been found to be better suited than voxels for geometrical deformation and shape adjustment owing to a richer set of computational operations (Xu *et al* 2007, Xu 2009). NURBS, for example, has shown to be capable of real-time cardiac and respiratory motion simulations (Segars *et al* 2001, Segars and Tsui 2002, Zhang *et al* 2008) although the anatomical accuracy sometimes is compromised by the priority given to real-time computation. In a previous work reported in 2007, a hybrid BREP method involving both NURBS and polygon mesh surfaces was adopted in the development of a series of RPI-pregnant (RPI-P) phantoms (Xu *et al* 2007). That experience led us to believe that the polygon mesh surfaces may be a better choice than the NURBS for developing deformable phantoms that can be controlled and processed automatically and rapidly without compromising the anatomical realism.

It is worth noting that under the current radiation protection dosimetry paradigm which is based on the ‘Reference Man’ concept, computational phantoms must contain anatomical parameters defined by the International Commission on Radiological Protection (ICRP) for average populations (ICRP 1975, 2002). However, several studies have suggested the need to account for body size, or specifically, the quantity of body fat present, when using computational phantoms to calculate radiation doses (Rannikko *et al* 1997, Kim *et al* 2003, Tung *et al* 2008, Xu *et al* 2008). Instead, an assembly of many phantoms representing different body sizes in terms of height and/or weight is needed. A recent study by Johnson *et al* (2009) at the University of Florida (UF) presented different sizes of the UF hybrid adult male (UFHADM) (Lee *et al* 2008) phantoms, corresponding to the body sizes of an underweight, average and overweight individual selected from a subset of individuals in the National Health and Nutrition Examination Survey III (NHANES III, 1988–1994) database, in three different (10th, 50th and 90th) percentile weights and with the same height as of the base UFHADM. These previous studies generally considered adjustments to the phantom size in two-dimensional planes and were concerned primarily with the quantity of subcutaneous fat.

In order to extend the feasibility of this approach to include not only body sizes but also internal organ volumes/masses for both male and female, this study takes advantage of recently developed polygonal mesh-based adult male and female phantoms (Zhang *et al* 2009). Although the ICRP reference phantoms are not a statistically rigorous average of any particular population, they are constructed from organs and tissues at the center of their size distributions. Since the magnitude of the height and weight distributions for ICRP data is unknown, the RPI phantoms adapt the anthropometric data for the 50th percentile of the US population for 19 year old males and females included in the updated NHANES (1999–2002) database, which correspond closely to the reference phantom values (McDowell *et al* 2005). In this paper, the term ‘deformable phantom’ is used interchangeably with ‘size-adjustable phantom’.

This paper first describes a comprehensive listing of anthropometric parameters and internal organ volume/mass values that cover the distribution of height and weight from the 5th to the 95th percentiles of the presumed worker population. Then, the paper shows how these values are used to deform the base RPI-AM and RPI-AF phantoms into new ones that match new percentile data using software algorithms. Finally, this paper presents a simple application of these phantoms for radiation transport simulations involving exposure to 0.5 MeV external photon beams.

2. Materials and methods

The schematic flowchart in figure 1 depicts the overall deformation process. In general, a deformable phantom includes two basic components: (1) base phantom(s) with anatomical parameters that match average or reference values and (2) a software tool that facilitates morphing the base phantom into a new one according to desired anatomical parameters. The software component is essential in the practical use of this set of deformable phantoms.

In this study, the computer software MATLAB[®] 7.4 was used to implement all of the computational algorithms used to create the size-adjustable phantoms. Previous experience has suggested that the polygonal mesh data structure is better suited for size-adjustable phantom modeling as compared to the voxel approach (Xu *et al* 2007). Therefore, this study was purposely designed to involve only mesh-based anatomical data.

2.1. RPI-AM and RPI-AF size-adjustable phantoms

The base phantoms for this study are a pair of polygonal mesh-based adult male and female phantoms known as the RPI-AM and the RPI-AF which were recently developed at Rensselaer (Zhang *et al* 2009). These phantoms were created from the Anatomium[™] 3D P1 organ mesh dataset and consist of over 140 deformable organs including their detailed internal organ boundaries with over 500 unique organ structures defined. The mesh data in RPI-AM and RPI-AF have been optimized and prepared for deformation. Adjustments were made to the original data to make these phantoms compatible with anatomical parameters matching the values specified by the ICRP Publications 23 and 89 (ICRP 1975, 2002). The individual organ masses of the RPI-AM (height: 176 cm, weight: 73 kg) and RPI-AF (height: 163 cm, weight: 60 kg) phantoms were carefully adjusted to agree within 0.5% relative error with the reference values (ICRP 2002). The deformation algorithms described later in this paper are applied to these two phantoms to derive new phantoms of desired parameters.

2.1.1. Percentile-specific whole-body sizes—The Centers for Disease Control and Prevention (CDC) has performed periodic surveys of the US population and the anthropometric reference data are available as the National Health and Nutrition Examination Survey (NHANES) (1999–2002). The report, released in 2005, provides the

height and weight data corresponding to the 5th, 10th, 15th, 25th, 50th, 75th, 85th, 90th and 95th percentiles. The height and weight survey data from the NHANES (McDowell *et al* 2005) of the US population for 19 year old males and females were adopted by this study as a primary reference for deforming the base RPI-AM and RPI-AF phantoms to obtain the 5th- to 95th-percentile RPI phantoms. The percentile distributions of the phantom size are used to correspond to the ICRP organ distribution information described in the following section. The missing multiples of five between the 5th and 95th percentiles were estimated using linear interpolation. The anthropometric parameters of height and weight percentile data for deforming the RPI mesh-based phantoms are shown in table 1 and figure 2. Using these data, the whole-body sizes in terms of weights and heights of the RPI-AM and RPI-AF mesh-based phantoms were adjusted by the appropriate factors applied to the whole-body of base phantoms including the skeleton (cortical bone, spongiosa, and medullary cavity structures) and internal organs. During this scaling process, the skeleton and organs were proportionally preserved in their positions inside of the body. These are then ready to be deformed by the specific organ percentile data described in the following sections.

2.1.2. Correlation between height and weight percentiles—The NHANES data presented in figure 2 do show the distributions of height and weight in the population without regards to each other. However, at each height point, there is a distribution in weight that is not explicitly provided in NHANES. It does, however, provide the population distributions in terms of the body mass index (BMI) as, defined by the CDC (2009):

$$\text{body mass index (BMI)} = \text{weight (kg)} / \text{height}^2 (\text{m}^2)$$

In this study, the distribution of body weight as a function of the height was estimated from the BMI values reported in the NHANES (1999–2002) (McDowell *et al* 2005). Figure 3 represents the RPI-AM and RPI-AF phantom after the weight percentiles have been adjusted according to different heights.

Due to the lack of data on the fat ratio of adult populations, the whole-body phantom was first scaled uniformly to achieve the desired height. In order to realistically depict individuals as underweight or overweight in the same height of phantoms, the skin surface for the desired weight was adopted from an open source software, MakeHuman™ version 0.9.1 RC11 (MakeHuman). The mass of each of the internal organs was then adjusted to the appropriate mass, with residual body fat making up the difference.

2.1.3. Percentiles of internal organs—After the whole-body size adjustments in height and weight, most major organs were deformed to match the organ-specific percentile data which are compiled from various sources. The percentile data for most major internal organs were based directly on the ICRP Publications 23 and 89 (ICRP 1975, 2002). It was assumed that the distribution of major internal organ volume and mass follows the Gaussian normal distribution (Na *et al* 2009b). The percentile data of each major internal organ were then derived from the cumulative pattern analysis for a normal distribution (Zelen and Severo 1972). As an example, table 2 shows the means and standard deviations (SD) for the lung mass values of the adult male and female.

The probability density function (PDF) of individual organ masses was derived from the given mean and standard deviation according to equation (1). The cumulative distribution function (CDF) in equation (2) gives the probability that the random variable of the certain organ size is less than or equal to a given percentile according to the PDF with Gaussian error function as defined by equation (3). The PDF was derived from the mean and standard deviation of volume and mass with the variation of each specific organ:

$$\text{PDF} = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}. \quad (1)$$

$$\text{CDF} = \int_{-\infty}^x \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx = \frac{1}{2} \left[1 + G \left(\frac{x-\mu}{\sigma \sqrt{2}} \right) \right], \quad (2)$$

where μ is the mean, σ is the standard deviation (SD) and the Gauss error $G(x)$ is defined as

$$G(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt, \quad (3)$$

where $t = (x - \mu) / \sigma \sqrt{2}$.

Figures 4(a) and (b) display a plot of PDF and CDF of the lung mass values of the adult male and female constructed using the data from table 2.

Table 3 lists all the right and left lung masses of adult male from the 5th to 95th percentile derived from the displayed cumulative distribution functions. The lung volumes could be estimated by the given density of the lung (0.25 g cm^{-3}).

In order to estimate the organ-specific percentile data for major internal organs, the same methodologies were used according to the organ ID numbers. In each summary of key organs, the organ volume and mass values in terms of means and standard deviations are listed for easy comparison with information in table 4.

Deformation is difficult for the organs closely located inside certain bone structures (e.g., eyes, spinal cord and inner-tongue). For this reason, through the initial whole-body size adjustment in each different percentile, the shapes of these organs were simultaneously morphed and changed by the adjacent skeletal surfaces. The volume and mass values of the morphed organs were then calculated and regarded as the corresponding percentile organ values.

2.2. Software tool for automated deformation

2.2.1. Organ volume calculations—Since the organ boundary deformation is quantified and controlled by the organ volume, it is critical to develop a reliable algorithm for determining the organ volume. For a solid volume of 3D organ meshes, all the surface-normals of each face must be oriented in the outward-pointing direction as described in figure 5. The key to calculating the volume defined by a triangular mesh is to decompose it into several elementary tetrahedrons (Ohanian 2005). Figure 6 depicts an example of a mesh volume calculation involving a simplest polyhedron and a tetrahedron, with vertices. Note how the geometry is decomposed into four different tetrahedrons with the same origin V_0 which is $\{0, 0, 0\}$: $\{V_0, V_1, V_3, V_2\}$, $\{V_0, V_1, V_2, V_4\}$, $\{V_0, V_3, V_2, V_4\}$ and $\{V_0, V_3, V_1, V_4\}$.

The volume of a single tetrahedron, $\{V_0, V_1, V_3, V_2\}$, can then be calculated with the following equation:

$$|\text{Volume}_{V_0,1,3,2}| = \left| \frac{1}{6} (-X_3 Y_2 Z_1 + X_2 Y_3 Z_1 + X_3 Y_1 Z_2 - X_1 Y_3 Z_2 - X_2 Y_1 Z_3 + X_1 Y_2 Z_3) \right|. \quad (4)$$

In general, to calculate the volume of a closed triangular mesh of arbitrary shape, the mesh can be decomposed into many tetrahedral sub-volumes. Then by using equation (4), the volumes of each of these tetrahedrons can be summed to obtain the volume of the original triangular mesh following equations (5) and (6):

$$\text{Volume}_i V'_i = \frac{1}{6}(-X_{i3}Y_{i2}Z_{i1} + X_{i2}Y_{i3}Z_{i1} + X_{i3}Y_{i1}Z_{i2} - X_{i1}Y_{i3}Z_{i2} - X_{i2}Y_{i1}Z_{i3} + X_{i1}Y_{i2}Z_{i3}). \quad (5)$$

$$\text{Volume}_i V'_i = \sum_i \text{Volume}_i V'_i, \quad (6)$$

where i is the index of elementary tetrahedrons or triangles. Triangle i has the coordinates of vertices, $\{V_{i1}, V_{i1}, V_{i1}\}$, $\{V_{i2}, V_{i2}, V_{i2}\}$, and $\{V_{i3}, V_{i3}, V_{i3}\}$ which are ordered in such a way that the triangle surface normals are consistent with each other (Zhang and Chen 2001).

2.2.2. Deformation algorithms—The RPI-AM and RPI-AF phantoms were used as the starting point for the development of percentile-specific adult male and female phantoms on demand. The first step in the deformation process is to match the reference organ volume data in the phantom with desired volume and mass values for a new phantom. There are two possible approaches to mesh deformation operations. One approach involves the multiplication of a uniform scale factor to ‘every’ vertex. This method yields a uniformly scaled mesh which keeps the overall mesh shape and reduces or increases the mesh volume. The other approach involves the multiplication of a unique scalar to ‘each’ vertex along the direction of normals. In our applications, the latter approach was used primarily for the elastic deformation for skeletal structured meshes while maintaining both the position and reference volume information. Then, the other organs were deformed in both approaches with a priority such as internal organs from the anatomical region from the chest to the abdomen (Na *et al* 2009a, Zhang *et al* 2009).

Each deformation operation is an iterative process in which ‘acceptance criteria’ of relative error, typically 0.5%, in the adjusted organ volume is used. To achieve this small volume error, both the uniform scale factor and the unique scalar were evaluated using Newton’s method, a well-known numerical analysis iterative technique (Deuflhard 2004). A solution that meets the acceptance criteria was found with the minimal computational cost. Once the desired mesh volume and deformation factors had been chosen for a user-defined ‘acceptable error,’ all organ meshes were automatically deformed to match organ-specific percentile volume data. The center of mass of each organ is kept constant during this deformation process (Zhang *et al* 2009).

2.2.3. Collision detection to avoid organ overlaps—The mesh-based RPI-AM and RPI-AF phantoms used in this work contained more than 140 organs or tissues. As these mesh models are deformed to the desired anatomical characteristics, it is essential to avoid overlap of adjacent organs. Surface collisions were detected and corrected using an algorithm based on the ray-casting method (Amanatides and Choi 1997). The first step in this approach was to designate every vertex point as the origin of a ray with the normal pointing from one organ surface to the other. Next, the distance between the origin and the reflecting point of the ray on an adjacent organ surface was calculated. Two surfaces were considered to be in collision if the distance between two mesh-surfaces was less than a pre-determined value, such as 3 mm used for this study as shown in figure 7. After a surface collision has been detected, the colliding vertex (denoted as a $\otimes$ mark in figure 7) 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 matches to the target value (Na *et al* 2009a).

This procedure assumes that one of the two adjacent organs has a higher priority in a collision. The ‘priority organ’ can expand its volume while the other organ gives way without changing its volume. Ideally, the organ deformation method should take into account pointwise, physics-based tissue elasticity. In this study, however, the organ density information recommended by ICRP was used to determine the priority of deformation between two organ surfaces. Less dense organs were assumed to give way in a collision to more dense organs. (i.e. a softer organ gives way to a harder one).

2.3. Monte Carlo dose calculations

2.3.1. Procedure to convert mesh-based geometry to voxel phantoms—

Currently, most Monte Carlo codes do not directly handle mesh-based geometries. Hence, to utilize a deformable phantom in Monte Carlo dose calculations, the mesh-based geometry must be converted to voxels. The RPI-AM and RPI-AF phantoms were converted to voxels with dimensions of 3.0 mm and 2.5 mm for a male and female, respectively. The relative errors in the final organ masses are less than 0.1% except for small organs such as eye lens. A software tool has been developed in Visual C++ using parity-counting and ray-stabbing methods for polygonal surface meshes which are closed or watertight (Zhang *et al* 2009). The ray-stabbing method is suitable for closed meshes, but the parity-counting method was also used in this process for certain tissues, such as the vessels and muscles, which are composed of open meshes. Figure 8 shows a typical task designed to verify the accuracy of the conversion by inspecting the skeleton and internal organs before and after the mesh voxelization process.

2.3.2. Monte Carlo simulations for absorbed organ doses—The final step of the workflow summarized in figure 1 is to link the voxel phantom with tissue density and elemental composition information (ICRU 1992) so that radiation transport through the phantom can be modeled correctly in a Monte Carlo code. In this study, the Monte Carlo N-Particle eXtended (MCNPX) code was used for organ dose calculations (Pelowitz 2005). The absorbed organ doses for the external photon exposures in the anterior–posterior (AP) direction with different percentile phantoms were calculated and compared. Each specific organ’s elemental composition was based on the reference values in ICRP Publication 89. For this paper, we considered 0.5 MeV photon energy. The MCPLIB04 cross-sectional library for the atomic interactions based on EPDL 97 evaluation was used. For electron transport, the standard library EL03 was used.

3. Results and discussions

3.1. Deformable phantoms

The ICRP 89 reference adult data were chosen as the 50th percentiles of the RPI-AM and RPI-AF phantoms deforming to different percentile individuals based on the height and weight data of NHANES (1999–2002). The 50th percentile data regarding the heights and weights of the NHANES adults, however, do not exactly fall at the ICRP reference adults, but the 50th percentile of 19 year old males and females was nearly close to the both reference values. Moreover, the differences of height and weight values between adults and 19 year old males and females on the NHANES are a narrower breakdown by age for adults (McDowell *et al* 2005). In this study, the height and weight percentile data of the RPI-AM and RPI-AF were based on the 50th percentile values of 19 year old males and females from NHANES. Since the deformation is based on software methods, this set of data can be easily adjusted in the future using different anthropometric references.

Individual organ volume and mass values within the 5th- to 95th-percentile range have been defined. Using uniform heights of 176 cm (males) and 163 cm (females), figure 9 shows the 5th-, 25th-, 50th-, 75th- and 95th-weight-percentile male and female phantoms representing individuals with variation in body weight, while the heights are kept the same. The skin of the phantoms was preprocessed to yield manifold meshes before being deformed to match the desired volume and mass. Most organ positions were proportionally kept at the same locations in the deformed RPI-AM and RPI-AF phantoms; the entire body weight was adjusted by reducing or adding fat under the skin.

When both the height and weight change, there are many possible combinations, making the management of these data and corresponding phantoms difficult. Figure 10 presents the RPI-AM and RPI-AF height and weight percentile phantoms that are designed to represent the estimated 5th-, 50th- and 95th-height and -weight percentiles based on table 1. The individual organ percentile data of the phantoms are classified according to the body size in terms of height and weight. Table 5 summarizes the organ masses for the RPI-AM and RPI-AF size-adjustable phantoms in our study.

The entire organ deforming process was completed automatically within 5 min on a PC operated on Intel® Centrino® Duo CPU of 2 GHz with 1 GB of RAM. The percentile-specific phantoms have the same number of organs and muscles as well as the bone structures (52 internal organs, 4 set of muscles, 45 bone structures), as the RPI-AM and RPI-AF phantoms for 50th percentiles.

3.2. Monte Carlo calculations

The calculations of absorbed organ doses involved three adult male phantoms representing the 5th-, 50th- and 95th-height and -weight percentiles—165, 176 and 188 cm in height and 56, 73 and 110 kg in weight—respectively. In the MCNPX simulations, each of these phantoms was irradiated by the 0.5 MeV broad external photon beams as shown in figure 11.

Absorbed organ doses from the 50th-height and -weight percentile phantom—one that resembles the Reference Man—were used to compare organ doses from the other two phantoms and the results are presented in figure 12 with 0.5 MeV phantom beams in AP irradiation geometry. It can be observed that the 5th-height and -weight percentile phantom receives higher absorbed organ doses than the 50th-height and -weight percentile phantom because of less photon attenuation from smaller amount of body fat in a slimmer and shorter individual male. In particular, the equivalent doses to the prostate and adrenal in the 5th-height and -weight percentile phantom are about 10% more than those in the 50th-height and -weight percentile phantom. By comparison, the 95th-height and -weight percentile phantoms resulted in a lower absorbed organ doses and the doses to the prostate and adrenal are approximately 20% smaller than those in the 50th-height and -weight percentile phantom. It is clear from the results that the variation in the body fat concentrated near the abdominal regions is responsible for the equivalent dose differences. Although not included in this paper, results for 1 MeV photon beams follow a similar trend as that shown in figure 12. The results suggest a general finding that phantoms representing a slimmer and shorter individual male received higher absorbed organ doses because of less photon attenuation due to smaller amount of body fat. However, more radiation types and various energies should be investigated in the future to fully understand the dosimetric differences in phantoms of difference sizes.

Several previous studies (Rannikko *et al* 1997, Kimet *et al* 2003, Tung *et al* 2008, Johnson *et al* 2009) presented the organ dose calculation results from the different weight phantoms but with the same height. In these studies, the 2D cross-sections including outer body skin

contour and organ contours inside the phantoms were proportionally modified or scaled to change the total weights of phantoms. Unlike these studies, the size-adjustable RPI phantoms are able to deform not only the body sizes in weight and height, but also their organ masses according to the different percentile data suggested by this study.

4. Conclusions

In this study, a detailed approach to the development of next-generation deformable phantoms covering different body heights and weights has been demonstrated. Comprehensive anthropometric references from the NHANES report (1999–2002) and ICRP Publications 23 and 89 were adapted to compile a range of body height and weight values. With mesh-based organ deformation algorithms, a new phantom can now be created, on demand, to match any desired volumes and masses included in the dataset. To demonstrate the feasibility for dose calculations, phantoms representing 5th-, 50th- and 95th-height and -weight percentiles were created and implemented in the MCNPX code to compare absorbed organ doses from 0.5 MeV photon beam irradiations. The results support a general finding that the phantoms representing a slimmer and shorter individual received higher absorbed organ doses because of lesser degree of photon attenuation by smaller amount of body fat.

This study has proposed a strategy for developing future phantoms that are deformable. These new phantoms rely on a deformation software component that works with a pair of base adult male and female phantoms of detailed mesh geometries. A new phantom is only created when needed, thus avoiding the burden of storing an overwhelmingly large amount of anatomical phantom data required to cover various body and organ sizes. Furthermore, in this approach, the anatomical details can be accurately and consistently persevered. In the future, the anatomical references may have to be updated to include the most recent information (such as when the ICRP modifies the list of critical organs). With the advantage of flexible deformation software methods demonstrated here, it is easy to update anatomical parameters. This study also suggests that, given person-specific anatomical information (even partial body information such as those from medical images), a new phantom can be created to reflect that person (for that portion of the body, plus the rest of the body not imaged), thus offering an opportunity to perform person-specific dosimetry for certain situations involving high radiation exposures. This approach will require image registration between patient images with the existing phantom and similar deformation algorithms described here. Recently, this approach was attempted by Alziar *et al* (2009) for assessing organ doses from radiation treatment. Finally, it should be pointed out that, since the deformation is performed with polygon mesh surfaces, developing ways in the future to perform Monte Carlo calculations directly in such geometry instead of converting to voxels will improve dose calculation.

Acknowledgments

This work was supported in part by grants from the National Cancer Institute (R01CA116743). The authors are grateful to Mr Matt Mille for reviewing the manuscript.

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Figure 1.
Flowchart of deformable mesh-based phantom modeling for Monte Carlo organ dose calculations.

Figure 2. Height and weight percentiles for the base RPI-AM and RPI-AF phantoms using data adapted from McDowell *et al* (2005). (a) Height percentiles, (b) weight percentiles.

Figure 3. Weight percentiles upon different heights for the RPI-AM and the RPI-AF using data adapted from McDowell *et al* (2005). (a) RPI-AM, (b) RPI-AF.

Figure 4. Statistical analysis for the lungs of the RPI adults: (a) probability density function (PDF); (b) cumulative density function (CDF).

Figure 5.

Vertex numbering and triangular surface normals in: common Edges $\overline{V_3V_2}, \overline{V_2V_4}$; Surface Normal $\vec{N}_{3,1,2}, \vec{N}_{4,3,2}, \vec{N}_{4,2,5}$; Faces(or triangles) $\Delta V_3V_1V_2, \Delta V_4V_3V_2, \Delta V_4V_2V_5$.

Figure 6.

Example of a simple polyhedron, where the V_0 is $\{0, 0, 0\}$; vertices: V_0, V_1, V_3, V_2 ; tetrahedron 1: $\{V_0, V_1, V_3, V_2\}$; tetrahedron 2: $\{V_0, V_1, V_2, V_4\}$; tetrahedron 3: $\{V_0, V_3, V_2, V_4\}$; tetrahedron 4: $\{V_0, V_3, V_1, V_4\}$.

Figure 7.

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

Figure 8. Visual inspection of the RPI-AM and RPI-AF base skeletons during the conversion from mesh geometry to voxel geometry. (a) Mesh format, (b) voxel format.

Figure 9. 3D front views of phantoms of the same height (males at 176.0 cm and females at 163.0 cm) but with different weight percentiles (5th, 25th, 50th, 75th and 95th) representing variation in the body: (a) the males (58.5 kg, 66.3 kg, 73.1 kg, 86.4 kg and 103.8 kg), (b) the females (46.5 kg, 55.8 kg, 64.0 kg, 78.9 kg and 95.9 kg).

Figure 10.

3D front views of the RPI 5th-, 50th- and 95th-height and -weight percentile male and female phantoms: (a) the males (165.0 cm, 176.0 cm and 188.0 cm in height, and 56.1 kg, 73.0 kg and 110.9 kg in weight, respectively), (b) the females (152.0 cm, 163.0 cm and 173.0 cm in height, and 41.0 kg, 60.0 kg and 91.0 kg in weight, respectively).

Figure 11. Phantoms representing workers of 5th-, 50th- and 95th-height and -weight percentile (weight: 56 kg, 73 kg and 110 kg, and height: 165 cm, 176 cm and 188 cm, respectively) exposure to 0.5 MeV phantom beams in AP irradiation geometry.

Figure 12.

Equivalent doses to organs in differences of 5th-, 50th- and 95th-height and -weight percentile (weight: 56 kg, 73 kg and 110 kg, and height: 165 cm, 176 cm and 188 cm, respectively) phantoms of irradiated by 0.5 MeV parallel photon beams in the geometry.

Heights (cm) and weights (kg) for the RPI-AM and RPI-AF size-adjustable phantoms using data adopted from McDowell *et al* (2005) of the US population for 19 year old males and females.

Table 1

Gender	Percentiles	5th	10th	15th	25th	50th	75th	80th	90th	95th
Male	Height (cm)	165.0	166.8	168.4	171.6	176.0	182.1	183.1	185.9	188.0
	Weight (kg)	56.1	58.1	60.9	65.2	73.0	86.7	91.0	102.4	110.9
Female	Height (cm)	152.0	153.7	155.4	158.0	163.0	168.2	169.3	171.7	173.0
	Weight (kg)	41.0	44.0	47.2	51.8	60.0	73.0	77.0	88.0	91.0

Table 2

Mean (μ) and SD (σ) values of lung masses for the RPI-AM and RPI-AF phantoms.

Gender	Left lung ($\mu \pm \sigma$)	Right lung ($\mu \pm \sigma$)
Male	553 $\pm$ 186(g)	647 $\pm$ 223(g)
Female	422 $\pm$ 129(g)	528 $\pm$ 189(g)

Table 3
Percentile values for mass and volume of the left and right lungs in the RPI adult phantoms.

Percentile	RPI-AM				RPI-AF			
	Lung mass (g)		Lung volume (cm ³)		Lung mass (g)		Lung volume (cm ³)	
	Left	Right	Left	Right	Left	Right	Left	Right
5th	247.06	280.20	988.24	1120.80	209.81	217.12	839.24	868.48
10th	314.63	361.21	1258.52	1444.84	256.68	285.79	1026.72	1143.16
15th	360.22	415.88	1440.88	1663.52	288.30	332.11	1153.20	1328.44
20th	396.46	459.32	1585.84	1837.28	313.43	368.93	1253.72	1475.72
25th	427.54	496.59	1710.16	1986.36	334.99	400.52	1339.96	1602.08
30th	455.46	530.06	1821.84	2120.24	354.35	428.89	1417.40	1715.56
35th	481.33	561.07	1925.32	2244.28	372.29	455.17	1489.16	1820.68
40th	505.88	590.50	2023.52	2362.00	389.32	480.12	1557.28	1920.48
45th	529.63	618.98	2118.52	2475.92	405.79	504.25	1623.16	2017.00
50th	553.00	647.00	2212.00	2588.00	422.00	528.00	1688.00	2112.00
55th	576.37	675.02	2305.48	2700.08	438.21	551.75	1752.84	2207.00
60th	600.12	703.50	2400.48	2814.00	454.68	575.88	1818.72	2303.52
65th	624.67	732.93	2498.68	2931.72	471.71	600.83	1886.84	2403.32
70th	650.54	763.94	2602.16	3055.76	489.65	627.11	1958.60	2508.44
75th	678.46	797.41	2713.84	3189.64	509.01	655.48	2036.04	2621.92
80th	709.54	834.68	2838.16	3338.72	530.57	687.07	2122.28	2748.28
85th	745.78	878.12	2983.12	3512.48	555.70	723.89	2222.80	2895.56
90th	791.37	932.79	3165.48	3731.16	587.32	770.21	2349.28	3080.84
95th	858.94	1013.80	3435.76	4055.20	634.19	838.88	2536.76	3355.52

Table 4

Mean and standard deviation (Mean $\pm$ SD) in major internal organ volume and mass values for the RPI adult phantoms.

ID	Organ name	RPI-AM (mean $\pm$ SD)		RPI-AF (mean $\pm$ SD)		Reference ^a
		Mass (g)	Volume (cm ³)	Mass (g)	Volume (cm ³)	
1	Adrenal (left)	7.00 $\pm$ 2.00	6.86 $\pm$ 1.96	6.50 $\pm$ 2.00	6.37 $\pm$ 1.96	(Tanaka <i>et al</i> 1979)
2	Adrenal (right)	7.00 $\pm$ 2.00	6.86 $\pm$ 1.96	6.50 $\pm$ 2.00	6.37 $\pm$ 1.96	
61	Brain	1450.00 $\pm$ 115.00	1394.23 $\pm$ 110.58	1300.00 $\pm$ 125.00	1250.00 $\pm$ 120.19	(Tanaka <i>et al</i> 1979) (Tipton and Cook 1969), (Dekaban and Sadowsky 1978), (IAEA 1998)
72	Stomach wall	150.00 $\pm$ 20.00	144.23 $\pm$ 19.23	140.00 $\pm$ 18.00	134.62 $\pm$ 17.31	(Tipton and Cook 1969)
75	Small intestine	650.00 $\pm$ 78.00	625.00 $\pm$ 75.00	600.00 $\pm$ 76.00	576.00 $\pm$ 73.08	(Tipton and Cook 1969)
76	Ascending colon wall	90.00 $\pm$ 14.00	86.54 $\pm$ 13.46	90.00 $\pm$ 15.00	86.54 $\pm$ 14.42	
78	Transverse colon wall (right)	60.00 $\pm$ 12.00	57.69 $\pm$ 11.54	55.00 $\pm$ 7.00	52.88 $\pm$ 6.73	
80	Transverse colon wall (left)	60.00 $\pm$ 12.00	57.69 $\pm$ 11.54	55.00 $\pm$ 7.00	52.88 $\pm$ 6.73	(Tipton and Cook 1969)
82	Descending colon wall	90.00 $\pm$ 23.00	86.54 $\pm$ 22.12	90.00 $\pm$ 15.00	86.54 $\pm$ 14.42	
84 and 86	Sigmoid colon and rectum wall	70.00 $\pm$ 12.00	67.31 $\pm$ 11.54	70.00 $\pm$ 12.00	67.31 $\pm$ 11.54	(Munn <i>et al</i> 1986), (Pavlik <i>et al</i> 2000), (Hongning <i>et al</i> 2001)
111	Ovary, left (female only)	N/A	N/A	5.50 $\pm$ 1.78	5.29 $\pm$ 1.71	(IAEA 1998)
112	Ovary (right) (female only)	N/A	N/A	5.50 $\pm$ 1.78	5.29 $\pm$ 1.71	(IAEA 1998)
113	Pancreas	140.00 $\pm$ 35.00	133.33 $\pm$ 33.33	120.00 $\pm$ 33.00	114.29 $\pm$ 31.43	(de la Grandmaison <i>et al</i> 2001) (IAEA 1998)
115	Prostate (male only)	17.00 $\pm$ 8.80	16.19 $\pm$ 8.38	N/A	N/A	(IAEA 1998)
127	Spleen	150.00 $\pm$ 29.00	141.51 $\pm$ 27.36	130.00 $\pm$ 20.00	122.64 $\pm$ 18.87	(Boyd 1933, 1941, 1952), (IAEA 1998)
132	Thyroid	20.00 $\pm$ 6.00	19.05 $\pm$ 5.71	17.00 $\pm$ 6.00	16.19 $\pm$ 5.71	(de la Grandmaison <i>et al</i> 2001)
139	Uterus (female only)	N/A	N/A	80.00 $\pm$ 8.00	76.19 $\pm$ 7.62	(Platt <i>et al</i> 1990)

^aICRP (1975, 2002) summarized several papers that provided information of organ-specific standard deviation (SD). The papers are listed below.

Table 5

List of organ masses for the RPL-AM and RPL-AF height and weight percentile phantoms.

ID	Organ name	RPL-AM organ mass (g) percentiles			RPL-AF organ mass (g) percentiles		
		5th	50th	95th	5th	50th	95th
1	Adrenal (left)	3.71	7.00	10.29	3.21	6.50	9.79
2	Adrenal (right)	3.71	7.00	10.29	3.21	6.50	9.79
3	Extrathoracic (ET)	30.31	39.44	59.92	12.73	18.61	28.25
5	Oral mucosa, tongue	23.82	31.00	47.09	6.15	9.00	13.66
7	Trachea	4.22	10.00	19.53	3.38	8.00	15.63
8	Bronchi	20.00	30.00	40.00	15.00	25.00	35.00
9	Blood vessels, head	0.65	0.85	1.29	4.14	6.06	9.20
10	Blood vessels, trunk	208.98	271.93	413.11	165.76	242.38	367.90
11	Blood vessels, arms	12.08	15.72	23.88	29.57	43.24	65.63
12	Blood vessels, legs	63.82	83.04	126.15	63.35	92.64	140.61
13	Humeri, upper half, cortical	103.93	135.26	205.46	76.89	112.60	170.66
14	Humeri, upper half, spongiosa	141.50	184.86	279.72	76.09	111.90	168.88
15	Humeri, upper half, medullary cavity	25.73	33.48	50.85	13.58	19.89	30.15
16	Humeri, lower half, cortical	98.38	128.03	194.48	69.78	102.21	154.88
17	Humeri, lower half, spongiosa	45.97	59.73	90.88	36.13	52.78	80.18
18	Humeri, lower half, medullary cavity	28.54	37.13	56.41	14.03	20.55	31.14
19	Ulnae and radii, cortical	208.08	270.80	411.33	105.94	155.14	235.13
20	Ulnae and radii, spongiosa	139.99	181.91	276.73	62.45	91.24	138.60
21	Ulnae and radii, medullary cavity	17.41	22.67	34.43	22.94	33.59	50.91
22	Wrists and hand bones, cortical	138.11	179.74	273.01	71.07	104.08	157.74
23	Wrists and hand bones, spongiosa	107.43	139.59	212.35	49.85	72.84	110.65
24	Clavicles, cortical	36.71	47.78	72.57	22.19	32.50	49.26
25	Clavicles, spongiosa	40.74	53.06	80.55	27.59	40.45	61.24
26	Cranium, cortical	432.49	562.85	854.95	275.58	403.60	611.65
27	Cranium, spongiosa	347.35	451.06	686.64	284.79	417.09	632.09
28	Femora, upper half, cortical	201.07	261.68	397.48	169.17	247.75	375.47
29	Femora, upper half, spongiosa	361.47	472.05	714.55	154.21	225.05	342.26
30	Femora, upper half, medullary cavity	19.82	25.78	39.16	26.98	39.51	59.88

ID	Organ name	RPI-AM organ mass (g) percentiles			RPI-AF organ mass (g) percentiles		
		5th	50th	95th	5th	50th	95th
31	Femora, lower half, cortical	225.97	294.09	446.71	158.73	232.47	352.31
32	Femora, lower half, spongiosa	337.51	438.57	667.20	119.55	174.67	265.34
33	Femora, lower half, medullary cavity	62.15	80.89	122.87	37.85	55.43	84.00
34	Tibiae, fibulae and patellae, cortical	408.29	531.35	807.11	422.55	618.85	937.86
35	Tibiae, fibulae and patellae, spongiosa	561.30	729.38	1109.61	401.45	586.52	891.02
36	Tibiae, fibulae and patellae, medullary cavity	60.45	78.67	119.50	59.85	87.65	132.83
37	Ankles and foot bones, cortical	178.70	232.56	353.26	117.27	171.75	260.27
38	Ankles and foot bones, spongiosa	390.78	507.78	772.49	185.04	270.35	410.70
39	Mandible, cortical	58.49	76.12	115.62	30.69	44.94	68.12
40	Mandible, spongiosa	56.88	73.90	112.43	23.69	34.67	52.59
41	Pelvis, cortical	306.30	398.62	605.50	177.43	259.84	393.80
42	Pelvis, spongiosa	522.24	681.18	1032.39	304.14	445.07	675.04
43	Ribs, cortical	280.67	365.16	554.85	111.21	162.87	246.83
44	Ribs, spongiosa	401.16	520.06	793.01	176.63	258.96	392.02
45	Scapulae, cortical	169.92	221.13	335.90	82.24	120.45	182.53
46	Scapulae, spongiosa	147.30	192.21	291.18	66.26	96.87	147.07
47	Cervical spine, cortical	79.08	102.92	156.33	48.40	70.88	107.43
48	Cervical spine, spongiosa	56.51	73.55	111.72	49.93	72.81	110.81
49	Thoracic spine, cortical	218.63	286.58	432.20	139.13	203.78	308.81
50	Thoracic spine, spongiosa	257.68	335.34	509.39	171.86	252.56	381.44
51	Lumbar spine, cortical	143.35	186.19	283.39	105.57	154.62	234.32
52	Lumbar spine, spongiosa	231.77	302.07	458.16	178.29	261.28	395.72
53	Sacrum, cortical	83.92	109.23	165.93	N/A	N/A	N/A
54	Sacrum, spongiosa	133.14	173.51	263.20	95.70	140.44	212.42
55	Sternum, cortical	7.60	9.89	15.03	1.14	1.67	2.53
56	Sternum, spongiosa	43.24	56.31	85.49	32.50	47.41	72.13
58	Cartilage	68.13	88.67	134.68	214.13	313.61	475.27
61	Brain	1260.84	1450.00	1639.16	1094.39	1300.00	1505.61
62	Breast (left), adipose tissue	5.76	7.50	11.39	53.63	150.00	246.44
63	Breast (left), glandular tissue	3.83	4.99	7.58	35.76	100.00	164.30

ID	Organ name	RPI-AM organ mass (g) percentiles			RPI-AF organ mass (g) percentiles		
		5th	50th	95th	5th	50th	95th
64	Breast (right), adipose tissue	5.76	7.50	11.39	53.63	150.00	246.44
65	Breast, right, glandular tissue	3.83	4.99	7.58	35.76	100.00	164.30
66	Eye lens (left)	0.15	0.20	0.30	0.14	0.20	0.30
67	Eye bulb, (left)	5.61	7.30	11.09	4.99	7.30	11.08
68	Eye lens (right)	0.15	0.20	0.30	0.14	0.20	0.30
69	Eye bulb (right)	5.61	7.30	11.09	4.99	7.30	11.08
70	Gall bladder wall	7.68	10.00	15.19	5.47	8.00	15.19
71	Gall bladder contents	44.88	58.00	88.72	32.80	48.00	88.72
72	Stomach wall	117.10	150.00	182.90	110.39	140.00	169.61
73	Stomach contents	195.17	250.00	304.83	181.35	230.00	278.64
75	Small intestine	802.62	1000.00	1197.38	696.65	880.00	1063.35
76	Ascending colon wall	66.97	89.99	113.03	65.33	90.00	114.67
77	Ascending colon contents	40.94	55.02	69.10	72.59	100.00	127.41
78	Transverse colon wall, right	40.26	60.00	79.74	43.49	55.00	66.52
79	Transverse colon contents, right	63.75	95.00	126.26	47.44	59.99	72.56
80	Transverse colon wall (left)	40.26	60.00	79.74	43.49	55.00	66.52
81	Transverse colon contents (left)	26.85	40.01	53.17	23.72	30.01	36.28
82	Descending colon wall	52.17	89.99	127.83	65.33	90.00	114.67
83	Descending colon contents	20.29	35.00	49.71	36.29	50.00	63.71
84	Sigmoid colon wall	28.73	40.01	51.30	32.32	45.01	57.70
85	Sigmoid colon contents	53.83	74.97	96.11	57.43	79.99	102.55
86	Rectum wall	21.53	29.98	38.44	17.94	24.99	32.04
87	Heart wall	253.60	330.00	501.33	170.83	250.00	379.17
88	Heart contents (blood)	391.93	510.00	774.78	252.83	370.00	561.17
89	Kidney (left), cortex	68.47	107.12	145.77	54.56	104.63	154.70
90	Kidney (left), medulla	24.45	38.25	52.05	19.49	37.37	55.25
91	Kidney, left, pelvis	4.88	7.63	10.38	3.90	7.48	11.06
92	Kidney (right), cortex	70.26	109.92	149.58	45.82	87.87	129.92
93	Kidney (right), medulla	25.09	39.25	53.41	16.36	31.38	46.40
94	Kidney (right), pelvis	5.00	7.87	10.66	3.27	6.28	9.27

ID	Organ name	RPI-AM organ mass (g) percentiles			RPI-AF organ mass (g) percentiles		
		5th	50th	95th	5th	50th	95th
95	Liver	1435.09	1800.00	2618.36	1009.06	1400.00	2037.85
97	Lung (left), tissue	247.06	553.00	858.94	209.81	422.00	634.19
99	Lung (right), tissue	280.20	647.00	1013.80	217.12	528.00	838.88
100	Lymphatic nodes, extrathoracic airways	1.74	2.26	3.43	0.92	1.34	2.03
101	Lymphatic nodes, thoracic airways	4.92	6.40	9.72	2.64	3.86	5.86
102	Lymphatic nodes, head	4.60	5.98	9.08	1.76	2.58	3.92
103	Lymphatic nodes, trunk	80.23	104.40	158.60	39.43	57.66	87.52
104	Lymphatic nodes, arms	6.02	7.83	11.90	2.67	3.90	5.92
105	Lymphatic nodes, legs	8.53	11.10	16.86	6.70	9.80	14.87
106	Muscle, head	935.99	1217.81	1850.30	274.68	401.97	609.65
107	Muscle, trunk	11 532.64	15 006.82	22 798.04	5820.79	8518.23	12 919.32
108	Muscle, arms	2113.76	2750.53	4178.55	1042.00	1524.87	2312.72
109	Muscle, legs	7704.12	10 024.97	15 229.72	4820.88	7054.94	10 699.99
110	Esophagus	25.20	40.00	54.80	21.84	35.00	48.16
111	Ovary (left) (female only)	N/A	N/A	N/A	2.58	5.50	8.42
112	Ovary (right) (female only)	N/A	N/A	N/A	2.58	5.50	8.42
113	Pancreas	82.43	140.00	197.57	65.72	120.00	174.28
114	Pituitary gland	0.46	0.60	0.91	0.41	0.60	0.91
115	Prostate (male only)	2.53	17.00	31.47	N/A	N/A	N/A
119	Residual tissue	16 504.88	21 004.29	33 300.46	16 619.88	24 341.27	38 012.62
120	Salivary glands (left)	35.00	42.50	50.00	28.75	35.00	41.10
121	Salivary glands (right)	35.00	42.50	50.00	28.75	35.00	41.10
125	Skin	2536.10	3300.00	5013.32	1572.90	2300.00	3491.07
126	Spinal cord	23.06	30.00	45.58	19.15	28.00	42.50
127	Spleen	102.30	150.00	197.70	97.10	130.00	162.90
128	Teeth	38.43	50.00	75.96	27.35	40.00	60.71
129	Testis (left) (male only)	13.45	17.50	26.59	N/A	N/A	N/A
130	Testis, right (male only)	13.45	17.50	26.59	N/A	N/A	N/A
131	Thymus	10.36	25.00	39.64	4.54	20.00	35.46
132	Thyroid	10.13	20.00	29.87	7.13	17.00	26.87

ID	Organ name	RPI-AM organ mass (g) percentiles			RPI-AF organ mass (g) percentiles		
		5th	50th	95th	5th	50th	95th
133	Tongue (inner part)	32.28	42.00	63.81	34.19	50.00	75.89
134	Tonsils	2.31	3.00	4.56	2.05	3.00	4.55
135	Ureter (left)	6.53	8.50	12.91	5.13	7.50	11.38
136	Ureter (right)	5.76	7.50	11.39	5.13	7.50	11.38
137	Urinary bladder wall	30.00	50.00	60.00	30.00	40.00	60.00
138	Urinary bladder contents	120.00	200.00	240.00	150.00	200.00	300.00
139	Uterus (female only)	N/A	N/A	N/A	66.84	80.00	93.16