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Assessment of PCXMC for patients with different body size in chest and abdominal x ray examinations: A Monte Carlo simulation study

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Abstract

A PC Program for X ray Monte Carlo (PCXMC) has been used to calculate organ doses in patient dosimetry and for the exposure assessment in epidemiological studies of radiogenic health related risks. This study compared the dosimetry from using the built-in stylized phantoms in the PCXMC to that of a newer hybrid phantom library with improved anatomical realism. We simulated chest and abdominal x ray projections for 146 unique body size computational phantoms, 77 males and 69 females, with different combinations of height (125 – 180 cm) and weight (20–140 kg) using the built-in stylized phantoms in the PCXMC version 2.0.1.4 and the hybrid phantom library using the Monte Carlo N-Particle eXtended transport code 2.7 (MCNPX). Unfortunately, it was not possible to incorporate the hybrid phantom library into the PCXMC. We compared 14 organ doses, including dose to the active bone marrow, to evaluate differences between the built-in stylized phantoms in the PCXMC and the hybrid phantoms (Cristy and Eckerman, 1987; Eckerman and Ryman, 1993; Geyer *et al.*, 2014). On average, organ doses calculated using the built-in stylized phantoms in the PCXMC were greater when compared to the hybrid phantoms. This is most prominent in AP abdominal exams by an average factor of 2.4-, 2.8-, and 2.8-fold for the 10-year-old, 15-year-old, and adult phantoms, respectively. For chest exams, organ doses are greater by an average factor of 1.1-, 1.4-, and 1.2-fold for the 10-year-old, 15-year-old, and adult phantoms, respectively. The PCXMC, due to its ease of use, is often selected to support dosimetry in epidemiological studies; however, it uses simplified models of the human anatomy that fail to account for variations in body morphometry for increasing weight. For epidemiological studies that use PCXMC dosimetry, associations between radiation-related disease risks and organ doses may be underestimated, and to a greater degree in pediatric, especially obese pediatric, compared to adult patients.

Keywords

Dosimetry; Epidemiology; Hybrid Phantom Library; MCNPX; Monte Carlo; PCXMC

I. Background

Individualized organ dose estimates for patients undergoing medical x ray examinations are one of the critical components in epidemiological investigations of the health risks associated with radiation exposure. Compared to experimental dose measurements, a computational approach requires fewer man-hours and is better suited to handle a large number of patients with various unique exposure conditions. A PC Program for X ray Monte Carlo (PCXMC) is one of the computational solutions to estimate organ doses for medical x ray examinations (Tapiovaara and Siiskonen, 2008a). Based on the Monte Carlo radiation transport method, the program calculates organ absorbed dose to a series of computational human phantoms, surrogates for patient anatomy, with the user-specified inputs of x ray machine parameters and patient age, height, and weight. The software has been used in several epidemiological and risk projection studies of cancer risk in patients undergoing x ray examinations (Zenone *et al.*, 2012; Baysson *et al.*, 2015; Harbron *et al.*, 2015; Baysson *et al.*, 2013; Harbron *et al.*, 2016; Ladia *et al.*, 2015). Researchers at the National Cancer Institute have also used the PCXMC to estimate medical radiation doses from over eight decades of diagnostic radiation procedures (Melo *et al.*, 2016; Chang *et al.*, 2017). However, the built-in computational phantoms in the PCXMC are a set of pediatric and adult stylized phantoms developed at Oak Ridge National Laboratory (ORNL) in the 1980s (Cristy and Eckerman, 1987). The PCXMC phantoms have two potential limitations for accurate dosimetry: over-simplified anatomical structures and unrealistic adjustment of body size.

Since the 1980's, computational human phantoms have evolved from simplified stylized phantoms to more realistic voxel phantoms to hybrid (or boundary representation) phantoms (Xu, 2014). In contrast to the stylized phantoms, in which the body contour and internal organs are described by simple mathematical equations, the voxel and hybrid phantoms are based on computed tomography or magnetic resonance images of patients for improved realistic anatomy. In addition to the anatomical realism, the hybrid phantoms also provide flexibility to change organ dimension and location. Several studies have underscored the dosimetric limitations of the stylized phantoms in external x ray exposure scenarios when compared to the voxel or hybrid phantoms with improved anatomical realism (Johnson *et al.*, 2011; Kramer, Khoury, and Vieira, 2008; Park, Lee, and Lee, 2007).

The second limitation in the PCXMC phantoms is over-simplified adjustment of body size. The program uniformly increases or decreases the length of the minor and major axis of an elliptical cylinder to simulate changes in the torso contour. The developers of the PCXMC note that the program is unable to account for the variability in adipose tissue distribution throughout the human body (Tapiovaara and Siiskonen, 2008a). Recent developments in the library of body size dependent hybrid phantoms can better account for morphometry of the patient population (Geyer *et al.*, 2014). In the current study, we conducted organ dose calculations in chest and abdominal x ray examinations by using two sets of computational human phantoms: the built-in stylized phantoms in the PCXMC and the body size dependent hybrid phantoms. We then compared the results to evaluate differences in dosimetry between the two phantom sets with varying body size.

II. Materials and Methods

We calculated organ doses from simulated chest and abdominal x ray examinations on two sets of computational human phantoms with varying body size: the built-in stylized phantoms in the PCXMC version 2.0.1.4 (Tapiovaara and Siiskonen, 2008a) and the body size dependent hybrid phantoms (Geyer *et al.*, 2014) combined with a general purpose Monte Carlo code, the Monte Carlo N-particle eXtended v2.7.1 (MCNPX) (Pelowitz, 2011). Details about different components in the Monte Carlo organ dose calculations are described in the following sections.

A. X ray spectra

The x ray spectra used in the Monte Carlo simulations were generated based on the standard radiation quality series (RQR) to best represent the radiation qualities incident on the patient from general radiography (IAEA, 2007). The RQRs are characterized by peak tube potential, half-value layer (HVL) in mm of aluminum (Al) equivalent, and the homogeneity coefficient. For the chest examinations, *equivalent spectra*¹ to the RQRs 4 and 6 were used when simulating pediatric examinations while *equivalent spectra* to RQRs 7 and 9 were reserved for adult examinations. *Equivalent spectra* to RQRs 6 and 7 were used for both pediatric and adult abdominal examinations (Bontrager and Lampignano, 2010).

The process to generate *equivalent spectra* to the RQRs differed between the PCXMC and MCNPX codes. We used the built-in spectrum generator in the PCXMC whereas the spectra was explicitly defined by photon energy and intensity for the MCNPX simulations. In the PCXMC, the peak tube potential and total filtration amount are required to use the built-in spectrum generator. In the version of the PCXMC used in this study, users are allowed to define up to two simultaneous filters of arbitrary atomic number and thickness. The PCXMC then generated the x ray spectra according to the theory of Birch and Marshall in 1 keV energy bins (Birch and Marshall, 1979). In order to create *equivalent spectra* to the RQRs defined in Table I the values for inherent filtration and added filtration in mm of Al were used according to Franciscatto *et al.* (de Penha Albuquerque Potiens and Franciscatto, 2009).

For the MCNPX simulations, we generated *equivalent spectra* to RQRs using the information from Table I, namely the peak tube potential and first HVL in mm of Al. This task was performed by iteratively hardening an initial soft spectra, generated with a tungsten anode spectral model using interpolating polynomials (TASMIP), through a chosen material as described by Turner *et al.* This approach does not assume prior knowledge of the actual spectrum or filtration scheme (Turner *et al.*, 2009; Boone and Seibert, 1997; Siewerdsen *et al.*, 2004). Rather, an initial spectrum with an inherent filtration of 1.6 mm of Al was used as the input and subsequently hardened to yield an *equivalent spectrum* (Boone and Seibert, 1997). The *equivalent spectrum* was then incorporated into the MCNPX input using the general source definition card, *SDEF*, in 1 keV energy bins along with the relative weight at each bin. We then compared the spectrum set from TASMIP with those from PCXMC to make sure both calculations are based on similar x ray spectra.

¹In this study, the term equivalent spectra is used to describe a computationally generated spectra based on values of peak tube potential, HVL, and/or filtration.

B. Computational human phantoms

The PCXMC uses the family of hermaphrodite stylized phantoms developed by Cristy and Eckerman with some modifications to the head and neck area as discussed in Eckerman *et al.* (Cristy and Eckerman, 1987). These phantoms incorporate only three different tissue types: skeleton, lung, and remaining soft tissues. We used the body size adjustment feature of the PCXMC to simulate 146 individuals with varying height (125 – 180 cm) and weight (20 – 140 kg). The body size adjustment is performed by multiplying all coordinates of a reference stylized phantom with a scaling factor to create the transformed phantoms, these scaling factors for the z- and xy-axis are defined in Equations 1 and 2 (Tapiovaara and Siiskonen, 2008a).

$$S_z = \frac{h}{h_o} \quad 1$$

$$S_{xy} = \sqrt{\frac{h_o \times M}{h \times M_o}} \quad 2$$

In Equations 1 and 2, h_o and h are the reference height of the phantom and desired height, respectively. Likewise, M_o and M denotes the reference and desired weight, respectively. The PCXMC provides a reference stylized phantom for the newborn, 1-, 5-, 10-, 15-year-old, and adult. For this study, only the 10-year-old, 15-year-old, and adult reference phantoms were used when matching height and weight to the hybrid phantoms used in Table II since the younger phantoms (1- and 5-year-old) may not show noticeable variations in body size.

To compare with the built-in stylized phantoms in the PCXMC, we employed a comprehensive library of body size dependent hybrid phantoms (Geyer *et al.*, 2014). The entire library consists of 351 unique computational phantoms that are binned by height and weight to represent the pediatric and adult populations. The hybrid phantom library traces its origins to the hybrid phantoms with reference body size (Lee *et al.*, 2009) that were then morphed to match the reference organ volume reported in ICRP Publication 89 and finally non-uniformly scaled to match body morphometry data from the National Health and Nutrition Examination Survey (NHANES) conducted by the Centers for Disease Control and Prevention (CDC) over the 1999–2006 time period (Geyer *et al.*, 2014). In contrast to the simplified torso model of the PCXMC stylized phantoms, which are represented by uniformly scaled elliptical cylinders, a more realistic curvature of the torso contours is modeled in the hybrid phantom library based on the anthropometric measurements of seven different body parts: height, weight, sitting height, and the circumferences of waist, thigh, arm, and buttocks. We selected a total of 146 unique hybrid phantoms out of the 351 phantoms to cover a range of body mass index (BMI) from underweight to obese individuals with varying height (125 – 180 cm) and weight (20 – 140 kg) as outlined in Table II. The distribution of BMI for the 146 phantoms is depicted in Figure 1.

C. Simulations of radiographic projections

We simulated a posteroanterior (PA) chest and anteroposterior (AP) abdominal radiograph examination on phantoms using the PCXMC and MCNPX codes. In both the PCXMC and MCNPX simulations, the x ray examinations were simulated using a point source that emits photons to match an energy spectra, field-of-view (FOV), collimation, and source-to-surface distance (SSD) common to clinical scenarios. The source-to-image receptor distance (SID) was not considered as there is no image receptor in the simulations. The values chosen for SSD, FOV, and collimation were matched to the anatomical landmarks on the phantom being modeled in the Monte Carlo simulation.

A description of the anatomical landmarks used in the x ray examinations are provided in Table III and are based on the text from Bontrager and Lampignano (Bontrager and Lampignano, 2010). The diverging x ray field for both the PA chest and AP abdominal exams was set to fully encompass the width of the ribcage. The height for the PA chest exams encompassed the length of the lungs while in the AP abdominal projection the length was set to equal to the distance between the base of the lungs and the pubic symphysis. We made the central ray lie on the sagittal plane and parallel to the transverse plane.

An a priori decision was made to define the FOV, collimation, and SSD using the anatomy of the hybrid phantoms and then used as the input for the PCXMC calculations which make use of the stylized phantoms. This is done, in part, because we assumed the hybrid phantoms to be the a more anatomically realistic set of phantoms and because we are unable to access the geometry files of the built-in stylized phantoms in the PCXMC. This process was automated for a total of 292 unique field sizes by using tag numbers of each voxel. In the hybrid phantoms, tag numbers are uniquely assigned to all voxels that belong to particular organ or tissue, 136 tag numbers in total. The tag system allowed us to locate spatial information for an organ of interest (*e.g.*, center-of-mass, boundary regions, and depth) by searching for all voxels of a given tag number and subsequently use that information to build the irradiation geometry in the Monte Carlo simulations. The field sizes and SSDs defined by the hybrid phantoms were then used as inputs to define the x ray fields on the built-in stylized phantoms in the PCXMC. The x ray field was centered on the anatomy of interest by specifying a reference point in the PCXMC. The reference point defines the x and z coordinates of the central ray, which lies on the y-axis. The location of the reference point was determined by solving the set of equations provided by Cristy and Eckerman and scaling the results by the factors defined in Equations 1 and 2.

The x ray field that was simulated in the current study is visualized for both the PA chest and AP abdominal examinations of the adult male stylized phantom used in the PCXMC for a phantom of 175 cm in height and 65 kg body weight, see Figures 2(a) and 2(b), using the built-in visualization feature for the PCXMC. A similar visualization of the x ray field on the hybrid phantom is shown in Figures 2(c) and 2(d). The chest and abdominal x ray beams have a FOV at the surface of 23.86 cm $\times$ 29.4 cm (width $\times$ height) and 24.41 cm $\times$ 21.90 cm, respectively. That is, were the same for both types of phantom. A total of 146 phantoms were used in each of the PCXMC and MCNPX simulations to model PA chest and AP abdominal exams for a total of 292 unique field sizes, 1168 simulations in total, to match the criteria described in Table III.

D. Organ dose calculations

The main focus of this study was to compare the impact of different methods for body size adjustment on the reported organ dose. This effect is unavoidably entangled with systematic differences in the Monte Carlo radiation transport algorithms which are hard-coded into the PCXMC and MCNPX software. One way to gauge the differences between the two Monte Carlo algorithms would be to perform identical simulations using the same phantom geometry in each of the codes. Unfortunately, such a one-to-one comparison was not possible because the hybrid phantoms cannot be easily incorporated into PCXMC and the exact geometry of the stylized phantom used in the PCXMC is unknown. The best comparison possible was to implement the ORNL adult male stylized phantom described by Cristy and Eckerman (Cristy and Eckerman, 1987) into the MCNPX code. We assume the ORNL phantom will closely match the built-in stylized phantom in PCXMC, but understand that there could still be some differences in the phantom geometries.

After checking for agreement between the two Monte Carlo codes using the ORNL stylized phantom, we calculated organ doses for the 146 phantoms with varying body size using the PCXMC for the stylized phantoms and the MCNPX code for the hybrid phantom library. Key assumptions and methods adopted in the PCXMC and MCNPX codes are summarized in Table IV. We calculated energy deposition across 14 organs and tissues including the lung, pericardium, urinary bladder, stomach, pancreas, liver, spleen, kidneys, adrenals, esophagus, gallbladder, thyroid, brain, and active bone marrow. The energy deposition tallies were then normalized to a kerma area product (KAP) meter reading of 1 mGy*cm². To facilitate the comparison of a large number of organ doses and as a measure of overall energy deposition the root mean square of organ doses (μ_{rmsd}) was used. The root mean square dose was calculated using organs with an energy deposition above 1% of the maximum organ dose thus eliminating organs that are far from the FOV edge and limiting the percent relative error, corresponding to one standard deviation, to be on average less than < 1%. Organs far from the FOV edge are likely to have tally convergence relative errors in excess of 10%.

III. Results

A. Comparison of x ray spectra used in PCXMC and MCNPX calculations

The parameters used to generate *equivalent spectra* for each RQR value are summarized in Table I (IAEA, 2007). The average photon energy, $\bar{E}$, in the PCXMC-generated equivalent spectra are slightly higher than the values of the spectra used in the MCNPX code but never by more than 2%, see Table I. Overall, the energy spectra generated using the PCXMC agreed with those created for the MCNPX simulations at the 5% significance level (Wilcoxon rank sum test, p-value=.45, .58, .67, .90 for RQRs 4, 6, 7, and 9, respectively). Figure 3 compares the equivalent spectra used in the PCXMC and MCNPX codes for RQRs 4 and 9. The peaks associated with the three most prominent k-shell characteristic x ray of tungsten are well defined in the spectra generated by the PCXMC, whereas the spectra for the MCNPX code have broader peaks that span multiple energy bins as seen in Figure 3(b). The spectra of the PCXMC are characterized with lower intensity at low energies and at the higher energies their intensity is greater than the spectrum generated for the MCNPX code.

B. Comparison of Monte Carlo transport methods between PCXMC and MCNPX

Table V compares the root mean square dose calculated for a PA chest projection on the ORNL stylized phantom using the PCXMC and MCNPX codes for three different field sizes. The field size of 24.41 cm width and 21.90 cm height (24.41×21.90) is equivalent to the field size calculated from the hybrid phantom of 175 cm height and 65 kg in body weight using the guidelines provided in Table III. The two additional field sizes of $25 \text{ cm} \times 25 \text{ cm}$ and $40 \text{ cm} \times 40 \text{ cm}$ illustrate the effect on the root mean square dose as a larger portion of the anatomy is irradiated. The mean dose of the organs agree within 8% and the PCXMC estimates of mean dose are consistently greater than the results of the MCNPX code. A bar plot highlighting these differences is shown in Figure 4 for the $24.41 \text{ cm} \times 21.90 \text{ cm}$ field size using an identical x ray spectrum in both the PCXMC and MCNPX codes that is equivalent to RQR 7.

C. Comparison of doses between the stylized and hybrid phantoms

For each unique simulation of an x ray examination, we calculated the ratio of the root mean square dose of the built-in stylized hermaphrodite phantom in the PCXMC to that of the hybrid phantom in MCNPX, see Figure 5 and 6. On average, the root mean square absorbed doses using the built-in stylized phantoms in the PCXMC are greater than dose estimates using the hybrid phantoms. This is most prominent in AP abdominal exams by an average factor of 2.4-, 2.8-, and 2.8-fold for the 10-year-old, 15-year-old, and adult phantoms, respectively. For chest exams, organ doses are greater by an average factor of 1.1-, 1.4-, and 1.2-fold for the 10-year-old, 15-year-old, and adult phantoms, respectively. The ratio of the root mean square dose exhibits a quadratic response to increases in BMI for both the male and female phantoms when irradiated in the abdominal AP projection (coefficient of determination, $r^2=0.933$, 0.950 , and 0.877 for the 10-year-old, 15-year-old, and adult male phantoms, respectively and $r^2=0.886$, 0.976 , and 0.861 for the 10-year-old, 15-year-old, and adult female phantoms, respectively) as shown in Figure 5(b) and 6(b). This correlation between BMI and ratio of the root mean square dose is weaker for chest PA examinations, see Figure 5(a) and 6(a). Results of the Monte Carlo energy deposition tallies on the hybrid phantom are reported in the Supplement Table VI.

In this study, we found an increased median ratio of active bone marrow (ABM) dose for the built-in stylized phantoms in the PCXMC to dose estimates using the hybrid phantoms. For abdominal radiographs this ratio was 1.18 and 1.39 (Wilcoxon-rank sum test, $p < .001$) for normal and obese weight phantoms, respectively. Likewise, for chest radiographs these ratios are 1.37 and 1.46 ($p = .044$) for the normal and obese weight phantoms, respectively. No significant difference, at the 5% significance level, in these ratios is observed when comparing abdominal and chest radiographs among phantoms of obese BMI.

IV. Discussion

The differences in the x ray spectra between the PCXMC and MCNPX simulations can be explained by how the spectra were generated. The PCXMC uses the semi-empirical model of Birch and Marshall whereas the empirical model of TASMIP was used in the MCNPX simulations. The Birch and Marshall method used Green's formula to insert the

characteristic x rays while the TASMIP method relies on fitting the highest order polynomial possible on measured x ray spectra (Green and Cosslett, 1968). Previous studies have quantified the percent difference in the ratio of total characteristic x rays to the sum of all x rays produced in the computational models against measured data and this percent difference is greater in spectra generated by the Birch and Marshall method than TASMIP (12.8 % to 1.4 % at 80 kVp and 5.0 % to 4.5 % at 120 kVp for Birch and Marshall and TASMIP methods, respectively) (Ay *et al.*, 2005). Ay *et al.* also noted that all semi-empirical models based on Birch and Marshall display a lower intensity at low energies ($E < 68$ keV) when compared to measured spectra, and a higher intensity at the higher energies. TASMIP had good agreement with measured spectra. In Table V, it is shown that these discrepancies between spectra minimally impact dose estimates ($< 2\%$).

For large scale studies, automation facilitates and improves the throughput of dose estimates. By using the voxel tag system in the hybrid phantoms it was possible to automate several of the technical parameters (*e.g.*, SSD, collimation, central ray location, etc.) required as input parameters for the simulation of x ray exams. Many of these same processes proved difficult when using the stylized phantoms in the PCXMC. Unlike the hybrid phantoms, the organs and body contours of the stylized phantoms used in the PCXMC were defined by mathematical expressions. Determining the location of the reference point, to center the x ray field, required solving these mathematical expressions, which are not provided in the PCXMC software. We had to use the mathematical equations described in the ORNL report by Cristy and Eckerman in lieu of the PCXMC documentation. We did not rely on the PCXMC to determine field size at the surface because that information was determined based on the anatomy of the hybrid phantoms. To address these issues, the PCXMC manual suggests using the graphics capabilities, see Figure 2, to locate the reference point which can be cumbersome for a large number of radiographic projections.

On average, the root mean square absorbed dose estimates using either the PCXMC or MCNXP code were within 6% of each other for the stylized phantom, see Table V. Because it was not possible to export the built-in stylized phantoms in the PCXMC directly into the MCNPX code, we had to assume that the ORNL adult phantom described in the ORNL report was identical to the PCXMC phantoms. However, it is mentioned in the PCXMC manual that “some modifications of the head, correction of some apparent errors in the data of Cristy and Eckerman and inclusion of some new organs: extrathoracic airways, oral mucosa, prostate and salivary glands” have been made (Cristy and Eckerman, 1987; Tapiovaara and Siiskonen, 2008b). The possible differences in anatomical geometry may have contributed to the difference seen between the PCXMC and MCNPX simulations, but other factors such as the cross section libraries and transport parameters may be likely contributors.

The main effect of the age of the anchor phantoms, direction of height scaling, sex, BMI, and site of radiographic examination on the root mean square dose ratio of the stylized phantoms in the PCXMC to that of the hybrid phantoms is shown in Figure 7. The effect of anchor phantom ($\Delta(\mu_{rmsd})_{HYBRID}^{STYLIZED} = 0.419$), direction height scaling

($\Delta(\mu_{rmsd})_{HYBRID}^{STYLIZED} = 0.026$), and sex ($\Delta(\mu_{rmsd})_{HYBRID}^{STYLIZED} = 0.184$) is when compared to BMI

category ($\Delta(\mu_{rmsd})_{HYBRID}^{STYLIZED} = 1.149$) and radiographic site ($\Delta(\mu_{rmsd})_{HYBRID}^{STYLIZED} = 1.475$).

These differences may be explained by how the excess adipose tissue is distributed in the stylized phantoms used by the PCXMC to that of the body size dependent hybrid phantom library. The stylized phantoms in the PCXMC distributes the excess adipose tissue by applying a set of uniform scaling factors to all coordinate points of a reference weight phantom, *i.e.*, the adipose tissue is homogeneously distributed throughout the phantom. In contrast, the hybrid phantoms distribute the adipose tissue to match morphometry data from the NHANES database providing a more realistic resemblance to the United States population while also better accounting for sex differences (Geyer *et al.*, 2014; Rothman, 2008; Geer and Shen, 2009). In accordance with morphometry data, the heavier hybrid phantoms have excessive adipose tissue in the anterior abdominal region when compared to the chest. As the weight of a phantom is increased, the depth, as measured from the anterior end, of an abdominal organ increases at a faster rate for a hybrid phantom than for a stylized phantom. For this reason, heavier phantoms provide increasingly greater shielding to at-depth abdominal organs, meaning an increase in the root mean square dose ratio, in the hybrid phantom when compared to the stylized phantoms as seen in Figure 5 and 6. The trend in increasing root mean square dose ratio as the BMI is increased is not as pronounced for the chest projections due both to the x ray field being in the PA direction and the decreased rate by which adipose tissue accumulates in the chest as phantom mass increases. In the abdominal projections, for the underweight adult phantom, Figure 8(a) and 9(a), the higher mean absorbed dose computed in the stylized phantom when compared to the hybrid phantom is driven by the bladder, stomach, and gallbladder; however, some organs in the hybrid phantom such as the pancreas, kidneys, and adrenals have a higher energy deposition than the stylized phantom. As the phantom mass is increased from underweight to a normal weight and finally to an obese phantom the trend is to increase the root mean square dose ratio. This trend is also true for the pediatric series of phantoms of 15 years of age, Figure 8(b) and 9(b), and for 10-year-old phantoms, Figure 8(c) and 9(c).

The normalized organ doses for abdominal projections are plotted in Figure 8 and 9 for the 10-, 15-year-old and adult phantoms at BMI ranging from underweight to obese. The organ doses to the bladder, stomach, esophagus, and gallbladder are always greater when computed on the stylized phantom as opposed to the hybrid phantom and the magnitude of this discrepancy increases as the mass of the phantom increases. Organs like the pancreas, liver, spleen, kidneys, and adrenals are greater in the hybrid phantom when compared to the stylized phantom for underweight phantoms; however, the reverse of this pattern is true at greater BMIs. For all cases, the normalized organ dose decreases as the weight of the phantom increases and for lower radiation qualities.

For studies analyzing the risk of radiogenic hematopoietic malignancies it is important to determine the absorbed dose to the hematopoietically active cells of the bone marrow. The use of the built-in stylized phantoms in the PCXMC for ABM dosimetry will, on average, be higher than estimates using the hybrid phantoms. This effect becomes more pronounced for phantoms of obese BMI; however, for the obese, it is insensitive to the two radiographic sites tested in this study. The observation of increasingly overestimating the ABM dose with BMI is attenuated when compared to the trends observed for the rise in the root mean square

absorbed dose estimates as a function of BMI. We believe this attenuation is due to the spatial distribution of ABM throughout the body; however, we acknowledge that this relationship is further complicated by differences in cellularity of the ABM as a function of age.

In this study, no assessment of accuracy was performed for either method of body size adjustment, only the impact of these two methods on the reported organ dose is studied. The assessment of accuracy is limited by the lack of patient-specific phantoms, constructed from tomographic images of the patient anatomy, to compare with our entire hybrid phantom library. Furthermore, in this study we did not perform a cross-comparison using a field size based on the built-in stylized phantoms in the PCXMC. The decision to use the hybrid phantoms to delineate the field size was made given their improved anatomical realism. We are unable to quantify the degree of anatomical realism; however, earlier studies of the hybrid phantom library have reported accuracy to within 30% by matching the patient to a phantom of equal height and weight (Johnson *et al.*, 2011; Stepusin *et al.*, 2017). A cross-comparison using a field size based on the built-in stylized phantom is further complicated by the nature in which PCXMC stores the geometry files, they are not amenable to automation. For epidemiological studies, this work underscores differences in estimates of exposure assessment between using the built-in stylized phantoms in PCXMC and the more anatomically realistic hybrid phantom library.

V. Conclusions

Our findings suggest that while the PCXMC is a useful organ dose calculator for x ray exams, the built-in stylized phantoms in the PCXMC homogeneously distribute excess adipose tissue throughout the phantom without regards to morphometry data of the population. The PCXMC may significantly overestimate the organ doses in abdominal exams of normal to obese patients, particularly for pediatric patients. Use of PCXMC in epidemiologic studies may underestimate the relationships between estimated organ doses and disease risks because a 1-unit (kg/m²) difference in BMI equals a much greater difference in dose estimated from PCXMC than dose estimated from the hybrid phantom model. This underestimation may be greater for obese versus normal-weight patients. Furthermore, how the PCXMC stores the phantom geometry data limits the ability to facilitate a large batch of irradiation scenarios which often is the case in epidemiological investigations of medical exposure to patients.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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(a)Adult

(b)Pediatric

FIG. 1.
Distribution of Body Mass Index for the pediatric and adult phantoms used in this study.

FIG. 2.

Visualization of the size and location of x ray field on the adult phantom of 175 cm height and 65 kg. The field for (a) PA chest and (b) AP Abdomen on the stylized phantom is the simulated radiograph generated with the PCXMC software (Tapiovaara and Siiskonen, 2008b). The field for (c) PA chest and (d) AP Abdomen on the hybrid phantom.

(a) Standard radiation quality RQR 4

(b) Standard radiation quality RQR 9

FIG. 3.

Relative intensity of the equivalent x ray spectra for (a) RQR 4 and (b) RQR 9 used in the Monte Carlo simulations in the PCXMC and MCNPX.

FIG. 4.

Comparison of absorbed dose to 11 organs between the ORNL adult phantom and the PCXMC for a posteroanterior chest x ray examination. Absorbed doses are normalized to a kerma-area product meter reading of $1 \text{ mGy} \cdot \text{cm}^2$. The equivalent spectra for a radiation quality of RQR 7 was used for this simulation with the field of view at the surface of the phantom of a width of 24.41 cm and a height of 21.90 cm.

FIG. 5.

The ratio of root mean square dose from the stylized phantoms in the PCXMC to those from the hybrid phantoms in MCNPX for the male phantoms at the age of 10, 15, and adult in (a) PA chest and (b) AP abdomen examinations.

FIG. 6.

The ratio of root mean square dose from the stylized phantoms in the PCXMC to those from the hybrid phantoms in MCNPX for the female phantoms at the age of 10, 15, and adult in (a) PA chest and (b) AP abdomen examinations.

FIG. 7.

The main effect on the ratio of root mean square dose, $(\mu_{rmsd})_{HYBRID}^{STYLIZED}$, from the age of the anchor phantom, height scaling, sex, body mass index (BMI), and radiographic site. BMI and radiographic site have a large impact on the $(\mu_{rmsd})_{HYBRID}^{STYLIZED}$ ($\Delta(\mu_{rmsd})_{HYBRID}^{STYLIZED} = 1.149$ and $(\mu_{rmsd})_{HYBRID}^{STYLIZED} = 1.475$, respectively) when compared to the effect of anchor phantom, direction of height scaling, and sex ($(\mu_{rmsd})_{HYBRID}^{STYLIZED} = 0.419$, $(\mu_{rmsd})_{HYBRID}^{STYLIZED} = 0.026$, and $(\mu_{rmsd})_{HYBRID}^{STYLIZED} = 0.184$, respectively).

(a)Adult male

(b)15-Year-old male

(c)10-Year-old male

FIG. 8.

Normalized organ doses for anteroposterior abdominal examinations from the PCXMC and MCNPX calculations for (a) 10-year-old, (b) 15-year-old, and (c) adult male phantoms ranging from underweight to obese. The absorbed dose is normalized to a kerma area product reading of 1 mGy*cm².

(a)Adult female

(b)15-Year-old female

(c)10-Year-old female

FIG. 9.

Normalized organ doses for anteroposterior abdominal examinations from the PCXMC and MCNPX calculations for (a) 10-year-old, (b) 15-year-old, and (c) adult female phantoms ranging from underweight to obese. The absorbed dose is normalized to a kerma area product reading of 1 mGy*cm².

TABLE I

Characteristics of x ray spectra generated for the Monte Carlo radiation transports.

Radiation quality ^a	Peak tube potential (kVp)	First HVL ^b (mm Al)	Homogeneity coefficient	Total filtration ^{c,d} (mm Al)	PCXMC $\bar{E}^e$ (keV)	MCNPX $\bar{E}^e$ (keV)
RQR 4	60	2.19	0.74	2.8	36.65	36.59
RQR 6	80	3.01	0.69	3.1	44.39	44.05
RQR 7	90	3.48	0.68	3.2	47.93	47.48
RQR 9	120	5.00	0.68	3.6	56.99	56.18

^aStandard radiation qualities from IAEA (2007)

^bHalf-value layer (HVL) in mm of aluminum equivalent

^cBase on values reported by de Penha Albuquerque Potiens and Franciscatto (2009)

^dAdded filtration specified in the PCXMC

^e $\bar{E}$ is the mean photon energy of the spectrum

TABLE II

Description of the hybrid computational phantoms used in this study.

Phantom series	Age (years)	Height (cm)	Weight range (kg)	Anchor phantom ^a
Pediatric	10	125	20–40	10M ↓
Pediatric	10	125	20–40	10F ↓
Pediatric	10	135	25–50	10M ↓
Pediatric	10	135	25–50	10F ↓
Pediatric	10	145	30–65	10M ↑
Pediatric	10	145	30–70	10F ↑
Pediatric	15	155	35–80	15M ↓
Pediatric	15	155	35–95	15F ↓
Pediatric	15	165	40–105	15M ↓
Adult	30	160	45–125	15F ↓
Adult	30	175	55–135	ADM ↓
Adult	30	165	45–135	ADF ↑
Adult	30	180	55–140	ADM ↑

^aThe phantom series was created by morphing a reference hybrid phantom, identified by age (10, 15, and *AD* for adult) and then the gender (*M* for male). The direction of height scaling is indicated by the arrow (↑ -up ↓ -down) (Geyer *et al.*, 2014).

TABLE III

Guidance for creating x ray projections on anatomy of the hybrid computational phantoms.

	Posteroanterior chest exams	Anteroposterior abdominal exams
Central ray	Central ray lies on the sagittal plane and is parallel to the transverse plane. The source was positioned 180 cm away from the point of exit of the x rays from the phantom. The central ray was centered between the base and apex of the lungs.	Central ray lies on the sagittal plane and is parallel to the transverse plane. The source was positioned 100 cm away from the point of exit of the x rays from the phantom. The central ray was approximately 5 cm above the crest of the iliac.
Collimation	The top and bottom border are level with the apex and base of the lungs. The lateral border is collimated to the outer margins of the ribcage.	The top and bottom border are level with the base of the lungs and pubic symphysis. The lateral border is collimated to the outer margins of the ribcage.
X ray spectra	Standard radiation qualities (RQR) 7 and 9 for adults and RQRs 4 and 6 for pediatric phantoms.	RQRs 6 and 7 for all phantoms.

TABLE IV

Assumptions and methods used in the two Monte Carlo radiation transport codes: MCNPX and the PCXMC

	MCNPX v2.7.1	PCXMC v2.0.1.4
Source description	The source is defined with the <i>SDEF</i> card as an anisotropic point source. The x ray beam is further collimated to produce a diverging rectangular field with the use of zero importance surfaces, i.e., surfaces that stop transporting all incident particles. The spectra is defined for at 1 keV bins up until the maximum peak tube potential.	The source is defined by the peak tube potential and up to two additional filters of arbitrary atomic number and thickness. Spectra is derived from the theory of Birch and Marshall (Birch and Marshall, 1979). Photons are emitted into a solid angle specified by the focal distance and and x ray beam dimensions (Tapiovaara and Siiskonen, 2008b).
Cross section libraries	ENDF/B-VII	Storm and Israel and Hubell <i>et al</i> (Storm and Israel, 1970; Hubbell <i>et al.</i> , 1975).
Transport parameters	Both photons and electrons were transported. The photon physics allowed for the generation of electrons and coherent scattering. The transport cut-off energy for electrons is set at 1 keV, after which their energy is locally deposited.	Photon transport in pcxmc models photoelectric absorption, and coherent scattering or incoherent scattering. Kinetic energy from all secondary electrons is locally deposited. Photons with energies less than 2 keV are locally deposited.
Variance reduction	No variance reduction was applied in this study	Photon weighting in photoelectric interactions and Russian roulette
Scored quantities	The F6 tally of energy deposition averaged over the cell of interest in units of MeV/g. This F6 tally was specified for all organs of interest and for a volume of air that represents the kerma-area product meter.	Energy deposition in various organs of the phantom
Number of histories and statistical uncertainty	The radiation transport was carried out until 5.0e8 particle histories were performed or until the computer time exceeds 50 hours. The relative errors in the energy deposition tally is less than 1% for all organs in the x ray field.	Particle histories were set to 200,000 and the relative errors in energy deposition scoring is below 5% for organs in the x ray field
Data post-processing	The energy deposition in the organs of interest was normalized to a kerma-area product reading of 1 mGy*cm ²	The energy deposition in the organs of interest was normalized to a kerma-area product reading of 1 mGy*cm ²

TABLE V
Root mean square of organ doses (RMDS) for the adult ORNL stylized phantom using the PCXMC and MCNPX

Radiation quality	BMI ^a	Imaging site	X ray spectra	FOV ^b at SSD ^c		RMDS		Ratio of RMDS
				Width (cm)	Height (cm)	PCXMC	MCNPX	
RQR7	22.95	Chest	different ^d	24.41	21.90	3.93×10^{-4} (0.21) ^e	3.70×10^{-4} (9.47×10^{-3})	1.06 (0.21)
				25	25	3.26×10^{-4} (0.28)	3.06×10^{-4} (0.01)	1.06 (0.28)
				40	40	2.27×10^{-4} (0.64)	2.11×10^{-4} (0.02)	1.08 (0.64)
			equal ^f	24.41	21.90	3.93×10^{-4} (0.21)	3.75×10^{-4} (9.48×10^{-3})	1.05 (0.21)
				25	25	3.26×10^{-4} (0.28)	3.11×10^{-4} (9.75×10^{-3})	1.05 (0.28)
				40	40	2.27×10^{-4} (0.64)	2.14×10^{-4} (0.02)	1.06 (0.64)

^aBody-mass index

^bField of view

^cSource to surface distance, *i.e.*, distance to the skin

^dTASMIP was used to generate spectra for MCNPX while the theory of Birch & Marshall was used for spectra in the PCXMC

^ePercent relative error corresponding to one standard deviation

^fBoth MCNPX and the PCXMC simulations used spectra generated from the theory of Birch & Marshall