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EVALUATION OF THE UF/NCI HYBRID COMPUTATIONAL PHANTOMS FOR USE IN ORGAN DOSIMETRY OF PEDIATRIC PATIENTS UNDERGOING FLUOROSCOPICALLY GUIDED CARDIAC PROCEDURES

Emily L Marshall, PhD^A,

J. Crayton Pruitt Family Department of Biomedical Engineering, University of Florida, Gainesville, FL

David Borrego, PhD^B,

J. Crayton Pruitt Family Department of Biomedical Engineering, University of Florida, Gainesville, FL

Trung Tran, BS,

J. Crayton Pruitt Family Department of Biomedical Engineering, University of Florida, Gainesville, FL

James C. Fudge, MD, and

UF Health Congenital Heart Center, Div. of Pediatric Cardiology, University of Florida, Gainesville, FL

Wesley E. Bolch, PhD

J. Crayton Pruitt Family Department of Biomedical Engineering, University of Florida, Gainesville, FL

Abstract

Epidemiologic data demonstrate that pediatric patients face a higher relative risk of radiation induced cancers than their adult counterparts at equivalent exposures. Infants and children with congenital heart defects are a critical patient population exposed to ionizing radiation during life-saving procedures. These patients will likely incur numerous procedures throughout their lifespan, each time increasing their cumulative radiation absorbed dose. As continued improvements in long-term prognosis of congenital heart defect patients is achieved, a better understanding of organ radiation dose following treatment becomes increasingly vital. Dosimetry of these patients can be accomplished using Monte Carlo radiation transport simulations, coupled with modern anatomical patient models. The aim of this study was to evaluate the performance of the University of Florida/ National Cancer Institute (UF/NCI) pediatric hybrid computational phantom library for organ dose assessment of patients that have undergone fluoroscopically guided cardiac catheterizations. In

FOR REPRINTS AND CORRESPONDENCE CONTACT: Wesley E. Bolch, PhD, PE, Department of Biomedical Engineering, University of Florida, Gainesville, Florida 32611-6550, Phone: (352) 273-0303 wbolch@ufl.edu.

^AEmily L. Marshall, PhD, Diagnostic Physics Residency Program, Department of Radiology, University of Chicago, Chicago, IL 60637

^BDavid Borrego, PhD, Division of Cancer Epidemiology and Genetics, National Cancer Institute, National Institutes of Health, 9609 Medical Center Drive, Bethesda, MD 20892

this study, two types of simulations were modeled. A dose assessment was performed on 29 patient-specific voxel phantoms (taken as representing the patient's true anatomy), height/weight-matched hybrid library phantoms, and age-matched reference phantoms. Two exposure studies were conducted for each phantom type. First, a parametric study was constructed by the attending pediatric interventional cardiologist at the University of Florida to model the range of parameters seen clinically. Second, four clinical cardiac procedures were simulated based upon internal logfiles captured by a Toshiba Infinix-i Cardiac Bi-Plane fluoroscopic unit. Performance of the phantom library was quantified by computing both the percent difference in individual organ doses, as well as the organ dose root mean square values for overall phantom assessment between the matched phantoms (UF/NCI library or reference) and the patient-specific phantoms. The UF/NCI hybrid phantoms performed at percent differences of between 15% and 30% for the parametric set of irradiation events. Among internal logfile reconstructed procedures, the UF/NCI hybrid phantoms performed with RMS organ dose values between 7% and 29%. Percent improvement in organ dosimetry via the use of hybrid library phantoms over the reference phantoms ranged from 6.6% to 93%. The use of a hybrid phantom library, Monte Carlo radiation transport methods, and clinical information on irradiation events provide a means for tracking organ dose in these radiosensitive patients undergoing fluoroscopically guided cardiac procedures.

Keywords

reference phantoms; hybrid phantoms; organ dosimetry; fluoroscopy; patient dosimetry

1. Introduction

Fluoroscopy provides a real-time physiologic visualization of internal organ structures. This real-time response mechanism provides continuous feedback to physicians as they perform lifesaving cardiac interventions. As such, cardiac catheterizations have long been accepted as the standard in both the assessment and treatment of pediatric patients with congenital heart defects (Feltz *et al* 2011). Nevertheless, secondary cancer risks are highest in these patients owing to the enhanced radiosensitivity of their tissues and their longer life expectancy over which effects may manifest. According to ICRP Publication 103, pediatric patients exposed to radiation at earlier stages of life experience 2–3 times the lifetime cancer risk compared to their adult counterparts (ICRP, 2007). At the same time, these procedures are typically life-saving in nature, and thus any secondary cancer risk must be properly viewed against their significant medical benefit.

Numerous agencies have voiced a need for comprehensive research into quantifying and understanding doses administered during pediatric interventional procedures; however, only a small number of institutions have taken on this task (UNSCEAR, 2013). Pediatric cardiac catheterization procedures are common in patients with congenital heart defects (CHDs). The abnormal anatomy in patients with CHDs results in complicated procedures resulting in longer fluoroscopy exposure times. In addition to abnormal anatomy, pediatric patients with CHDs typically undergo numerous procedures over their lifetime to either correct or provide an interim solution to the anatomic defect. As long-term outcomes for these pediatric CHD

patients improve, a better understanding of organ radiation dose following treatment becomes increasingly vital.

Current dosimetry methods for the estimation of organ dose include the collection of dose metrics in conjunction with dose conversion coefficients (DCCs) computed from Monte Carlo methods. The collected dose metrics range from the reference point air kerma ($K_{a,r}$) and kerma-area product (KAP), to less useful dose metrics such as fluoroscopy time (Balter, 2008; Yakoumakis *et al.*, 2013; Glatz *et al.*, 2014; Barnaoui *et al.*, 2014; Harbron *et al.*, 2015). DCCs are commonly computed using anatomical data based on computational hermaphroditic phantoms to represent human patient anatomy at limited specific ages: 0, 1, 5, 10, 15-years-old, and adults. Previous studies have shown the importance of patient-phantom matching in providing accurate dosimetry calculations. The use of stylized phantoms result in patient dose errors as large as 83% for various fluoroscopic projections (Johnson *et al.*, 2011).

In this study, we consider the performance of the University of Florida/National Cancer Institute (UF/NCI) hybrid phantom library in pediatric organ dosimetry for patients that have undergone a cardiac catheterization procedure. The UF/NCI phantom library includes 85 male and 73 female pediatric phantoms covering a range of height and weight representative of the United States population (Geyer *et al.*, 2014). The present study performs dosimetry on three different types of anatomical phantoms. These include (1) 29 patient-specific voxel phantoms derived from segmentation of computed tomography images (considered to provide ground truth values of patient organ dose), (2) height/weight-matched hybrid library phantoms, and (3) age-matched reference phantoms. Dosimetry estimates were derived using Monte Carlo radiation transport methods on each of the anatomical phantoms. The dosimetry portion of this study investigated both (1) a set of customized irradiation events¹ and (2) real clinical studies based on internal logfiles captured by a Toshiba Infinix Cardiac Bi-Plane fluoroscopic unit at UF Health. The set of custom irradiation events, under guidance by the attending pediatric interventional cardiologist at UF Health, models a range of parameters (*e.g.*, angulation, peak tube potential, amount of added filtration, etc.) most commonly seen in pediatric catheterization procedures. Dose accuracy was quantified by computing the percent difference in organ dose between the matched phantoms (UF/NCI library or reference) and the patient-specific phantoms.

2. Materials and Methods

2.1. Patient-specific phantom construction

The 29 pediatric patient-specific voxel phantoms were built from chest-abdomen-pelvis CT datasets of patients (ages 14 days - 18 years) acquired from the PACS system at the Department of Radiology, UF Health Jacksonville, under a HIPAA-compliant IRB-approved protocol (IRB #201400396). The CT datasets were loaded into the image segmentation software 3D-DOCTORTM (Able Software Corporation, Lexington, MA) for visual contouring of 10 internal organ and tissue structures (heart, lungs, liver, stomach, pancreas, spleen, kidneys, homogeneous skeleton, residual soft tissue, and bladder) along with the

¹An irradiation event describes a single depression of the fluoroscopy foot pedal and subsequent activation of the x-ray tube.

outer body contour. Once visual contouring of an entire dataset was completed, the 3D image sets were exported to the modeling software Rhinoceros™ (Robert McNeel and Associates, Inc, Seattle, WA) as a polygon mesh. The phantoms were subsequently voxelized at a resolution appropriate to their height and weight combination and converted to a lattice file structure for use in the MCNPX v2.7 radiation transport code (see Section 2.6) (Pelowitz, 2011; Borrego *et al.*, 2017).

2.2 Patient-dependent hybrid phantoms, morphometric matching, and anatomic modifications

Each of the 29 patient-specific voxel phantoms described above were morphometrically matched to a unique member of the UF/NCI hybrid phantom library. The library phantoms were matched to a patient-specific voxel phantom using the recorded total height and body weight of the imaged patient. When total height for a given patient was not available, phantom matching was then based upon patient torso length as determined in the Rhinoceros™ software and defined in this study as the distance between the apices of the third cervical vertebra (C3) and sacrum. If assessment of torso length was not possible due to incomplete CT scan length, phantom matching was then established based upon the distance between the apices of the first and tenth ribs.

The patient-specific voxel phantoms are an anatomical model of the patient's chest, abdomen, and pelvis. Resultantly, the matched UF/NCI library phantoms' arms were removed, and their torso anatomies were truncated so as to be consistent with the modeled anatomy of their patient-specific counterpart (see Figure 1). Table 1 displays the height and weight of each patient and identifies their matched UF/NCI library phantom, along with the resolution used for voxelization. The library phantoms are denoted by the acronyms UFHPPF or UFHPM (University of Florida Hybrid Pediatric Female or Male, respectively) with the two following numbers indicating that phantom's standing height (in cm) and the total body mass (in kg).

2.3 UF hybrid reference phantom study

Previous studies by Johnson *et al.* (2011) considered both stylized phantoms and UF hybrid reference phantoms in looking at associated differences in organ dosimetry for fixed fluoroscopic projections. Findings from this study showed an average relative difference in organ dose of up to 83% between adult reference phantoms and adult patient-specific voxel phantoms. Hybrid reference phantoms are created to match the 50th percentile height and weight at various reference ages: 0, 1, 5, 10, 15, and 30 years, respectively. Inclusion of this comparison in the Johnson *et al.* study illustrated the usefulness of body morphometry-matched hybrid phantoms over age-matched reference phantoms for dosimetry in fluoroscopically guided interventions. We included a similar comparison between the patient-specific pediatric voxel phantoms and their closest age-matched UF hybrid reference phantom as described by Lee *et al.* (2010). Patient-specific phantoms were matched to their appropriate hybrid reference phantom based exclusively on recorded age. Should a patient-specific phantom fall midway between two ages, the age was rounded up, e.g. a 3-year-old would be matched to a 5-year-old reference.

Absolute weight differences were computed between each patient-specific phantom and their nearest age-matched reference phantom. A maximum weight difference of 40.2% was observed for Patient #15. Patient-specific phantom #15 (male age 3 years) was matched to the UF 5-year-old male hybrid reference phantom. A minimum weight difference of 3.7% was for Patient #4. Patient-specific phantom #4 (female age 13 years) was thus matched to the UF 15-year female hybrid reference phantom.

2.4 Parametric study of pediatric FGI organ dosimetry

In this study, a set of irradiation events representative of a cardiac catheterization procedure was designed by Dr. James Curtis Fudge, Director of the Pediatric Interventional Catheterization Laboratory at the UF Health Congenital Heart Center. The irradiation events cover a range of body positioning, angulation, field of view (FOV), and beam quality observed in-clinic. In total, 12 different angle combinations were generated using variations in positioner primary angle (PPA) and positioner secondary angle (PSA) as defined by the 2014 DICOM standard (IEC, 2014). The angles used in the present study are listed in Table 2 with a visual aide provided in Figure 2. Red tick marks in Figure 2 correspond to the radiation source position, while the PPA/PSA values listed in Table 2 correlate to the location of the image receptor. The isocenter parameter for the irradiation events was varied over three locations enclosed within the heart as shown in Figure 3. Accordingly, the isocenters are defined at the midpoint of the heart (midsection position) and relative to the midpoint as being cranial and caudal to the midpoint (cranial and caudal position). The variation in the isocenter parameter is included to represent table motion during cardiac catheterization procedures. Finally, two diagnostic x-ray spectra were considered that cover the range of values for pediatric cardiac catheterization laboratories: 60 kVp and 120 kVp. The 60 kVp spectrum was filtered to meet CFR §1020.30(m)(1) regulations of a half value layer (HVL)² of 1.5 mm Al equivalent. The 120 kVp spectrum was filtered to yield an equivalent spectrum with a HVL of 11.5 mm Al equivalent, the maximum value observed by Cowen *et al.* (2013) in a catheterization laboratory. The set of irradiation events included all possible combinations of PPA, PSA, isocenters, and peak tube potential and is shown in Table 2. The set of irradiation events, 72 in total, was subsequently modeled at three different fields of view (FOV): $11.5 \times 11.5 \text{ cm}^2$, $22.9 \times 22.9 \text{ cm}^2$, and $45.9 \times 45.9 \text{ cm}^2$ defined at the image receptor plane for a total of 216 unique irradiation events. The entire series of irradiation events were simulated using a Monte Carlo radiation transport code on the patient-specific phantoms, height/weight-matched hybrid phantoms, and the age matched reference hybrid phantoms.

2.5 Clinical procedure study of pediatric FGI organ dosimetry

The UF Health Toshiba fluoroscopic unit used in this study (Model Infinix-I Cardiac Bi-Plane) is a legacy system and thus does not generate Radiation Dose Structured Report (RDSR) as per current DICOM standards (IEC, 2007, 2014). Nevertheless, the system generates a logfile for physics quality assurance purposes. The logfile records the angulation (PPA and PSA), image type ('Photo', 'F-rec', 'DSA')³, source-to-image receptor distance, tube potential, kerma area product, and coordinates of the table for each activation of the

²<https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?FR=1020.30>

imaging system, *i.e.*, an irradiation event. In addition to the information provided per irradiation event, the logfile includes the cumulative reference point air kerma ($K_{a,r}$) and cumulative kerma-area product (KAP) for the procedure. The logfile can be thought of as a pre-cursor to its modern day equivalent - the radiation dose structured report (IEC, 2007, 2014).

In this study, logfiles from four cardiac catheterizations were extracted, de-identified, and saved in compliance with Institutional Review Board (IRB) Protocol 2014-00396. The cumulative $K_{a,r}$ and kerma-area product were used to define an averaged square FOV for the procedure at the reference point ($\overline{FOV}_r$), as per Eq. 1:

$$\overline{FOV}_r = \left(\frac{KAP}{K_{a,r}} \right)^{1/2} \quad (1)$$

The reference point, for an isocentric fluoroscopic system, lies on central axis of the x-ray beam and at 15 cm from isocenter in the direction of the x-ray tube.⁴ Using this definition of $\overline{FOV}_r$, the corresponding FOVs at the detector for logfiles #1, #2, #3, and #4 are 14.6×14.6 cm², 13.2×13.2 cm², 20.5×20.5 cm², and 12.9×12.9 cm² respectively. Table 3 lists each logfile number and catalogues the patient-specific phantom to which the logfile was applied. Efforts were made to only select those logfiles performed on patients with similar habitus to an available patient-specific phantom. Procedural descriptions are included for reference. The geometry modeled in the radiation transport simulations is shown in Figure 4. As an example, Table 4 gives the specific parameters recorded for each of the 77 irradiation events to which patient #1 was exposed.

The Monte Carlo simulations included an equivalent x-ray spectrum to that produced by the fluoroscopic unit based on physical measurements of HVL. This beam characterization follows the methods outlined by Borrego *et al.* (2017) for fluoroscopically guided interventions. The clinical fluoroscopy unit made use of 3 different filter combinations (1.5 mm Al, 1.5 mm Al + 0.03 mm Ta, 1.5 mm Al + 0.06 mm Ta) during procedures. HVL measurements were taken on the unit for each of the 3 different added filter combinations at peak tube potentials of 50, 70, 100, and 110 kVp. A multiple linear regression model accounting for peak tube potential and added filtration was fitted to the measured HVL data points to predict HVL. An equivalent spectrum to clinical measurements was then generated by taking an initial computational candidate spectrum and iteratively hardening it to match the measured HVL for the amount of added filtration and peak tube potential reported by the Logfile. The equivalent spectra are generated using the libraries from the tungsten anode spectral model using interpolating polynomials in conjunction with Spektr™ (Boone and Seibert, 1997; Siewerdsen *et al.*, 2004; Turner *et al.*, 2009). Lastly, measurements were made to properly align the coordinate systems used by the fluoroscopic unit, and subsequently reported in the Logfile, to the coordinate system used in the Monte Carlo simulations. The

³Machine recordings were defined as follows: Photo represented a radiographic image, f-rec represented a fluoroscopic acquisition, and DSA represented digital subtraction angiography

⁴<https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?FR=1020.32>

information from the Logfile thus forms the basis for describing all Monte Carlo radiation transport simulations on a patient-specific voxel phantom, height-weight matched hybrid phantoms, and age-matched reference hybrid phantoms.

2.6 Radiation transport simulations

The radiation transport code MCNPX v 2.7.1 was used in this study (Pelowitz, 2011). MCNP is a well-established radiation transport tool for both medical and occupational radiation dosimetry applications, and is supported by the Los Alamos National Laboratory (<https://mcnp.lanl.gov>). Details of its application to the present study are given in Table 5. MCNP simulations were performed for three sets of phantoms: (1) patient-specific voxel phantoms, (2) morphometry-matched UF/NCI hybrid phantoms, and (3) age-matched UF hybrid reference phantoms, and for both (1) the set of 216 irradiation events shown in Table 2 for our parametric analysis study (Section 2.4), and (2) the 77, 147, 29, and 114 irradiation events from logfiles #1, #2, #3, and #4 respectively, in our clinical procedure study (Section 2.5).

2.7 In-field and out-of-field organ designation

For each phantom in this study - patient-specific, hybrid library, hybrid reference - the cumulative absorbed dose was computed for eight organs (heart, lungs, liver, stomach, pancreas, spleen, kidneys, and bladder). Both the lungs and kidneys were dose averaged. Organ doses were separated into two categories: organs primarily irradiated in-field and those primarily irradiated out-of-field. The four organs with the highest cumulative normalized organ dose were taken as primarily “in-field” at each irradiation event, while all other organs were assigned as primarily “outof-field”. This assignment was made individually for each phantom, each organ, and for each irradiation event. In this manner, the assignment of organs “in-field” was variable and changed with irradiation event angulation (PPA and PSA) and heart location at isocenter.

2.8 Percent difference calculations

Results for both the parametric study (Section 2.4) and clinical procedure study (Section 2.5) are given in terms of the magnitude of the percent difference in organ dose defined as:

$$|Organ\ Dose\ \% \ Difference| = \left| \frac{Organ\ Dose_{matched} - Organ\ Dose_{patient - specific}}{Organ\ Dose_{patient - specific}} \right| 100\% \quad (2)$$

Percent differences were assessed between those reported for the patient-specific voxel phantom and both the morphometry-matched UF/NCI hybrid phantoms and the age-matched reference hybrid phantom. As an example, Figure 5 displays the cumulative percent difference in organ dose between the patient-specific phantom for Patient #6 and her morphometry-matched UF/NCI hybrid phantom (see Table 1) as seen under all 72 irradiations events defined in Table 2 for a FOV of $11.5 \times 11.5\text{ cm}^2$ at the image receptor. The upper curve of Figure 5 (circles) represents the cumulative percent difference seen in “out-of-field” organs, while the lower curve (squares) represent that same quantity but for the “in-field” organs as defined in Section 2.7. It is observed that the differences in organ

dose between two phantoms (expressed as a percentage), changes during the procedure. At first, the differences are large, but as the number of irradiation events progressively increases, the organ dose differences decrease and stabilize to around 20% for infield organs, and to around 35% for out-of-field organs.

These cumulative percent organ dose differences were averaged across all 29 patients of the study. Table 6 shows a further breakdown comparing the percent organ dose differences after one irradiation event and the cumulative percent organ dose difference for all 72 irradiation events for all patients and all three FOVs. A similar analysis was made in comparing patient-specific voxel phantom to age-matched reference hybrid phantoms of the parametric analysis study, and between both sets of phantoms in the clinical procedure study. The clinical procedure study organ doses were also compared using a calculated root mean square dose (RMSD) to represent the phantoms “in-field” organ doses (displayed as $organ_{1-4}$) as a singular value. Calculation of one value, as a representation of the overall phantom in-field organ dose, enabled a more direct comparison of the dosimetry performances of the phantom cohorts. RMSD values were computed as:

$$Root\ Mean\ Square\ Dose\ (RMSD) = \sqrt{\frac{(organ_1)^2 + (organ_2)^2 + (organ_3)^2 + (organ_4)^2}{4}} \quad (3)$$

3. Results

3.1 Parametric study - performance of the UF/NCI hybrid phantom library

The parametric portion of this study was established to test the UF/NCI hybrid phantom library under a variety of clinical irradiation conditions. Percent differences in organ dose were computed at the completion of the final 72nd irradiation event for each of the 29 patients in the study. These aggregate results are shown in Figures 6 to 8 for each of the three FOVs in the parametric study and stratified by organ location relative to the x-ray beam, sex, and beam. In Figures 6 to 8, the bounds of the blue box represent the 25th and 75th percentiles (Q1 and the red line represents the median, and the black whiskers represent all data that fall within times the inter-quartile range (Q3-Q1). Data shown as filled circles are outliers that extend beyond that range.

All percent differences are reported for in-field organs unless otherwise stated. Table 7 lists each of the 29 patients' in-field organs. The average percent difference for in-field organ dose across all 29 patients for the smallest FOV ($11.5 \times 11.5\text{ cm}^2$) was 31.0% with a median value 28.2%. Patient #13 had the largest percent difference at 87%, while Patient #16 had the smallest percent difference at 12.5%. The average percent difference for the middle FOV ($22.9 \times 22.9\text{ cm}^2$) was 22.6% with a median value of 20.6%. Patient #24 displayed the largest percent difference a 56.0%, while Patient #15 had the smallest percent difference at 6.6%. The average percent difference for the largest FOV ($45.9 \times 45.9\text{ cm}^2$) was 15.4% with a median value of 14.2%. Patient #1 displayed the largest percent difference at 37.4%, while Patient #16 had the smallest percent difference at 5.2%.

3.2 Parametric study - performance of the UF reference hybrid phantoms

Reference phantoms were also considered in the parametric study to determine if a high degree of specificity in phantom morphometry is warranted. Figures 9 and 10 illustrate the performance of both the age-matched hybrid reference and height-weight matched hybrid phantoms in relationship to organ doses seen in the patient-specific phantoms. The smallest difference in weight between a patient-specific phantom and their matched UF hybrid reference phantom was observed in patient #4. Figure 9 compares the results of both the matched UF hybrid reference phantom and the patient-specific phantom #4. The UF 15-year-old hybrid reference phantom yielded percent differences in organ dose at 41.8%, 33.4%, and 17.6% for the smallest, intermediate, and largest FOVs, respectively, of the parametric study for Patient #4. Corresponding percent differences in organ dose were 27.6%, 20.6%, and 11.0% for the morphometry-matched UF/NCI hybrid phantom (UFHPF-165,55). Figure 10 compares results for the phantoms with the greatest divergence in total body weight, observed in patient #15. The UF hybrid reference 5-year-old phantom yielded percent differences in organ dose of 99.3%, 99.2%, and 99.0% for the smallest, intermediate, and largest FOVs of the parametric study for Patient #15. Corresponding percent differences in organ dose were 16.6%, 6.6%, and 15.3% for the morphometry-matched UF/NCI hybrid phantom (UFHPM-105,15).

3.3 Clinical procedure study - performance of the UF/NCI hybrid phantom library

In this portion of the study, logfiles from cardiac catheterization procedures were extracted from the Toshiba fluoroscopic unit to compare organ dosimetry between the UF/NCI hybrid phantom library in relation to organ doses seen in the patient-specific phantoms. RMSD values were computed to generate one overall organ dose value per phantom. The RMSD calculation places a greater weight on organs with a large energy deposition. For Logfile #1, with 77 irradiation events, the in-field RMSD percent difference between respective phantoms is estimated to be 7%. The corresponding in-field RMSD percent differences for Logfiles #2, #3, and #4 with 147, 29, and 114 irradiation events, respectively, were 14%, 29%, and 11%. Table 8 below displays the values of these in-field organs and their respective doses for both phantom types and their percent difference for each of the four logfiles.

4. Discussion

Our previous study demonstrated a consistent improvement in the accuracy of estimates of fluoroscopy-delivered organ doses with increasingly higher degrees of patient-specificity in computational phantom matching (Johnson *et al.*, 2011). The Johnson *et al.* study, however, was limited to adult procedures and to only four discrete fluoroscopic projections. The present study extends this work to include 29 pediatric patient-specific voxel phantoms with morphometry matching to an expanded UF/NCI hybrid computational phantom library.

4.1 Field-of-view

Figures 6 to 8 display cumulative percent differences in organ dose for all 29 patients over the three FOVs considered in the parametric study. The average values of percent difference in organ dose observed at each FOV displayed a gradual decline with increasing FOV (31%,

22.6%, and 15.4%, respectively). This trend in the cohort average percent difference with increasing FOV was further demonstrated individually for 20 of the 29 patients in the study. With larger irradiated areas of the patient's body, differences in internal phantom anatomy - patient-specific compared to that of the morphometry-matched UF/NCI hybrid phantom - become less significant and organ dose discrepancies lessen.

4.2 Number of irradiation events

Expanding on the single projection analysis by Johnson et al. (2011), the addition of multiple irradiation events is shown to decrease the percent difference in organ doses for a hybrid library phantom using a patient-specific phantom as the reference. In Figure 5 and Table 6, the cumulative percent difference in organ dose decreases, on average, with each additional irradiation event, a gradual improvement in phantom performance is realized. This trend was also seen best within the simulated clinical procedures for logfile #3. Logfile #3 was composed of the fewest number of irradiation events at 29 which resulted in an organ dose RMS percent difference of 28.6% between the patient-specific phantom and the morphometry-matched UF/NCI hybrid phantom. The remaining three logfiles were composed of irradiation events numbering 77 to 147 and displayed organ dose RMS percent differences of 6.9% to 13.9%.

4.3 Angulation and tube potential

The present study calculated a baseline error in organ doses of 15% to 30%. These values are lower than the baseline error of between 35% to 45% reported by Johnson et al. (2011) for its study of single fluoroscopic projections using an earlier and smaller library of adult hybrid phantoms. As the number of irradiation events increases, covering a wider range of angles, a more evenly distributed irradiation of the tissues is accomplished when compared to single projections. This effect attenuates errors due to organ misalignment between the hybrid phantom and patient-specific phantom. The degree of organ misalignment becomes less important as larger volumes of the phantom are irradiated with the addition of multiple angulations. Anatomical differences - between the matched phantoms (UF/NCI library or reference) and the real patient - are more critical for patient organ dosimetry under fluoroscopy than under computed tomography due to the more anisotropic irradiation geometry of the former. For example, Stepusin et al. (2017) has reported that the median baseline error seen in hybrid library phantoms undergoing CT imaging and following patient height/weight matching was on the order of 10%.

As shown in Figures 6–8, cumulative percent difference in organ doses were highest with the softer x-ray spectrum. At the lower photon energies, differences in organ depth, shape, and position accentuate organ dose discrepancies between the true anatomy (patient-specific phantoms) and the approximated internal anatomy (matched hybrid phantom).

4.4. Phantom matching

Figures 9 and 10 show the performance of the age-matched phantoms tested in this study. Following the validation study completed by Johnson et al. (2011), which presented a strong argument for the use of height and weight based phantoms, this study focused on testing the cohorts' extrema for age-matched phantoms. In the age-matched phantom most similar to

the patient-specific counterpart, the age matching performed at 18% to 42%, depending on the FOV. This can be compared to the morphometry-matching of the hybrid library phantoms, which performed at 11 to 28%. With even small changes in patient height and weight, large differences in organ doses become apparent. This effect can be attributed, in part, to slight differences in organ positioning and even organ volumes. For these reasons, the UF/NCI hybrid phantom library performs with marked improvement over their age-matched reference phantom counterparts.

5. Conclusions

This study assessed the ability of phantoms chosen from the UF/NCI pediatric hybrid phantom library to match the anatomy of pediatric patients undergoing cardiac catheterization procedures for the purpose of calculating organ doses. A reliable phantom library is the first step in providing accurate patient dose reports to physicians on a large scale. This study suggests that increased anatomical specificity seen in the morphometry-matched UF/NCI hybrid phantoms, significantly improves the accuracy of organ dosimetry over that provided by age-matched reference phantoms. The baseline error seen in the parametric portion of the study was ~ 15% to 30% as given by organ dose differences in the patient-specific and hybrid library phantoms. This result was further reinforced in our clinical procedure study which reported relative errors in organ dose RMS values of 7% to 29%.

As demonstrated recently by Borrego et al. (2017), the advantage of a hybrid phantom library, is in its ability to readily provide an anatomic model of the patient with all internal organ structures pre-defined as needed for radiation transport simulation of organ doses. These developments allow physicians to move past KAP readings and fluoroscopy time as patient dose metrics, and to directly provide a means of organ dose tracking in these radiosensitive pediatric patient populations. The clinical implications of a validated pediatric phantom library are important, providing a readily available platform for both prospective and retrospective dosimetry studies seeking to quantify patient organ dose in fluoroscopic cardiac interventional procedures.

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Figure 1.

Patient-dependent and patient-specific phantoms following anatomical modification for female Patient #2. (a) Patient-specific voxel phantom, and (b) height/weight matched UF/NCI female hybrid phantom UFHPF-125,20 where 125 is the standing height in cm and 20 is the total mass in kg. For visual clarification purposes only, organs not present in the corresponding patient-specific voxel phantom are not shown in the images of matched hybrid phantom.

Figure 2.

Angles used in the parametric portion of this study. Red tick marks denote the locations of the x-ray source. (a) view of the positioner primary angle (PPA) and (b) view of the positioner secondary angle (PSA).

Figure 3.
Heart centers at the (a) cranial position, (b) midsection position, and (c) caudal position.

Figure 4.
Geometry modeled in the radiation transport simulations.

Figure 5.

Scatter plot displaying the cumulative magnitude of the percent difference in organ dose for the morphometry-matched UF/NCI hybrid phantom with the patient-specific voxel phantom used as the reference for Patient # 6. The field of view at the image receptor was set to $11.5 \times 11.5 \text{ cm}^2$ field of view. Irradiation events defined in Table 2.

Figure 6.

Box plot of the cumulative percent difference in organ dose between the patient-specific and library hybrid phantoms averaged across all 29 patients of the parametric analysis study. Data are shown for the $11.5 \times 11.5 \text{ cm}^2$ FOV.

Figure 7.

Box plot of the cumulative percent difference in organ dose between the patient-specific and library hybrid phantoms averaged across all 29 patients of the parametric analysis study. Data are shown for the $22.9 \times 22.9 \text{ cm}^2$ FOV.

Figure 8.

Box plot of the cumulative percent difference in organ dose between the patient-specific and library hybrid phantoms averaged across all 29 patients of the parametric analysis study. Data are shown for the $45.9 \times 45.9 \text{ cm}^2$ FOV.

Figure 9.

Percent differences in organ dose between both the 15-year-old reference phantom and morphometry-matched UF/NCI hybrid phantom to the patient-specific phantom of Patient #4, aged 13 years.

Figure 10.

Percent differences in organ dose between both the 5-year-old reference phantom and morphometry-matched UF/NCI hybrid phantom to the patient-specific phantom of Patient #15, aged 3 years.

Table 1.

Patient demographic information of patient-specific voxel phantoms, morphometry-matched UF/NCI hybrid phantom, and their voxel resolution (cm).

Patient #	Age / Sex	Height (cm)	Weight (kg)	Matched UF/NCI Hybrid Phantom	Voxel resolution (cm)		
					x	y	z
1	2y F	88.5	13.6	UFHPPF-85,15	0.0663	0.0663	0.1400
2	6y F	40.0 *	21.7	UFHPPF-125,20	0.0990	0.0990	0.2425
3	7y F	42.1 *	26.9	UFHPPF-135,25	0.0990	0.0990	0.2425
4	13y F	160.0	52.6	UFHPPF-165,55	0.1260	0.1260	0.2700
5	13y F	47.3 *	60.0	UFHPPF-155,60	0.1200	0.1200	0.2828
6	14y F	45.8 *	44.9	UFHPPF-145,45	0.0990	0.0990	0.2425
7	15y F	172.7	65.8	UFHPPF-175,65	0.1260	0.1260	0.2700
8	15y F	170.0	70.0	UFHPPF-165,70	0.1260	0.1260	0.2700
9	16y F	167.6	56.7	UFHPPF-165,55	0.1260	0.1260	0.2700
10	16y F	175.3	68.0	UFHPPF-175,70	0.1260	0.1260	0.2700
11	17y F	160.0	50.8	UFHPPF-165,50	0.1260	0.1260	0.2700
12	18y F	160.0	70.0	UFHPPF-155,70	0.1260	0.1260	0.2700
13	14d F	53.3	5.0	UFH Newborn	0.0663	0.0663	0.0663
14	2y F	87.6	11.8	UFHPPF-85,10	0.0663	0.0663	0.1400
15	3y M	31.0 *	13.2	UFHPPM-105,15	0.0850	0.0850	0.1928
16	4y M	32.8 *	15.0	UFHPPM-105,15	0.0850	0.0850	0.1928
17	6y M	36.5 *	24.0	UFHPPM-115,25	0.0850	0.0850	0.1928
18	8y M	42.1 *	35.9	UFHPPM-145,35	0.0990	0.0990	0.2425
19	11y M	47.0 *	38.6	UFHPPM-155,40	0.1250	0.1250	0.2832
20	12y M	152.4	46.7	UFHPPM-155,45	0.1250	0.1250	0.2832
21	14y M	50.4 *	45.4	UFHPPM-155,45	0.1250	0.1250	0.2832
22	14y M	172.7	65.0	UFHPPM-175,65	0.1579	0.1579	0.2207
23	15y M	182.9	69.0	UFHPPM-185,70	0.1579	0.1579	0.2207
24	15y M	157.5	60.8	UFHPPM-155,60	0.1250	0.1250	0.2832
25	16y M	185.4	94.8	UFHPPM-185,95	0.1579	0.1579	0.2207
26	17y M	177.8	63.5	UFHPPM-175,65	0.1579	0.1579	0.2207
27	17y M	180.3	89.8	UFHPPM-185,90	0.1579	0.1579	0.2207
28	17y M	24.3 **	72.6	UFHPPM-175,75	0.1579	0.1579	0.2207
29	18y M	162.6	63.5	UFHPPM-165,65	0.1250	0.1250	0.2832

* Patient torso length (in cm);

** Length as measured from the top of 10th rib to top of 1st rib (in cm)

Table 2.

Individually labeled irradiation events utilized within the parametric study. Each event is shown along with their respective tube potential, heart location at isocenter, and both the PPA and PSA.

Irradiation Event	Energy (kVp)	Heart Location	PPA (deg)	PSA (deg)
1	120	cranial	90	0
2	120	cranial	0	0
3	120	cranial	-30	0
4	120	cranial	-25	0
5	120	cranial	-35	0
6	120	cranial	-20	0
7	120	cranial	0	-20
8	120	cranial	0	-22
9	120	cranial	0	-24
10	120	cranial	0	-26
11	120	cranial	0	-28
12	120	cranial	0	-30
13	120	midsection	90	0
14	120	midsection	0	0
15	120	midsection	-30	0
16	120	midsection	-25	0
17	120	midsection	-35	0
18	120	midsection	-20	0
19	120	midsection	0	-20
20	120	midsection	0	-22
21	120	midsection	0	-24
22	120	midsection	0	-26
23	120	midsection	0	-28
24	120	midsection	0	-30
25	120	caudal	90	0
26	120	caudal	0	0
27	120	caudal	-30	0
28	120	caudal	-25	0
29	120	caudal	-35	0
30	120	caudal	-20	0
31	120	caudal	0	-20
32	120	caudal	0	-22
33	120	caudal	0	-24
34	120	caudal	0	-26
35	120	caudal	0	-28
36	120	caudal	0	-30
37	60	cranial	90	0
38	60	cranial	0	0

Irradiation Event	Energy (kVp)	Heart Location	PPA (deg)	PSA (deg)
39	60	cranial	-30	0
40	60	cranial	-25	0
41	60	cranial	-35	0
42	60	cranial	-20	0
43	60	cranial	0	-20
44	60	cranial	0	-22
45	60	cranial	0	-24
46	60	cranial	0	-26
47	60	cranial	0	-28
48	60	cranial	0	-30
49	60	midsection	90	0
50	60	midsection	0	0
51	60	midsection	-30	0
52	60	midsection	-25	0
53	60	midsection	-35	0
54	60	midsection	-20	0
55	60	midsection	0	-20
56	60	midsection	0	-22
57	60	midsection	0	-24
58	60	midsection	0	-26
59	60	midsection	0	-28
60	60	midsection	0	-30
61	60	caudal	90	0
62	60	caudal	0	0
63	60	caudal	-30	0
64	60	caudal	-25	0
65	60	caudal	-35	0
66	60	caudal	-20	0
67	60	caudal	0	-20
68	60	caudal	0	-22
69	60	caudal	0	-24
70	60	caudal	0	-26
71	60	caudal	0	-28
72	60	caudal	0	-30

Table 3.

Summary of the logfiles extracted from the Toshiba unit including the patient-specific voxel phantom assigned to that particular clinical patient, the number of irradiation events recorded, and the clinical procedure performed.

Logfile Number	Patient # (see Table 1)	Number of irradiation events	Procedural description
1	11	77	Endomyocardial biopsy, coronary and aortic angiography
2	17	147	Balloon dilation of pre-existing pulmonary artery stent, and pulmonary artery angiography
3	19	29	Endomyocardial biopsy, superior vena cava angiography
4	15	114	Balloon dilation of pre-existing pulmonary artery stent, and pulmonary artery angiography

Table 4.

Irradiation event data from Logfile #1 including the tube potential, SID, PPA, and PSA.

Irradiation Event	Energy (kVp)	SID (cm)	PPA (deg)	PSA (deg)
1	80	93	1	0
2	80	93	1	0
3	80	98	1	0
4	80	96	1	0
5	80	94	1	0
6	80	98	1	0
7	80	98	1	0
8	80	98	1	0
9	80	120	90	0
10	80	100	0	0
11	80	100	0	0
12	80	120	90	0
13	80	100	0	0
14	80	100	0	0
15	80	120	90	0
16	80	100	0	0
17	80	120	90	0
18	80	100	0	0
19	80	100	0	0
20	80	120	90	0
21	80	100	0	0
22	80	120	90	0
23	80	100	0	0
24	80	120	90	0
25	80	100	0	0
26	80	100	0	0
27	80	100	0	0
28	80	100	0	0
29	80	100	0	0
30	80	100	0	0
31	80	100	0	0
32	80	100	0	0
33	80	100	0	0
34	80	100	0	0
35	80	100	0	0
36	80	120	90	0
37	80	100	0	0
38	80	100	0	0
39	80	120	90	0

Irradiation Event	Energy (kVp)	SID (cm)	PPA (deg)	PSA (deg)
40	80	120	90	0
41	80	111	0	0
42	75.82	111	0	0
43	82.29	120	90	0
44	80	111	0	0
45	80	105	0	0
46	80	120	90	0
47	75.86	105	0	0
48	87.18	120	90	0
49	80	105	0	0
50	80	105	0	0
51	80	105	0	0
52	80	105	0	0
53	80	105	0	0
54	80	105	0	0
55	80	105	0	0
56	80	105	0	0
57	80	105	0	0
58	80	105	0	0
59	80	105	0	0
60	80	105	0	0
61	80	105	0	0
62	80	105	0	0
63	80	105	0	0
64	80	105	0	0
65	80	105	22	20
66	80	105	3	2
67	80	120	90	0
68	80	120	90	0
69	80	105	0	2
70	79.31	105	0	2
71	97.51	120	90	0
72	80	107	22	-31
73	94.25	107	22	-31
74	80	107	-24	-18
75	83.32	107	-24	-18
76	80	107	-21	17
77	76.38	107	-21	17

Table 5.

Details of the radiation transport computations and data post-processing (Pelowitz, 2011).

Item	Description
Code and Version	MCNPX v2.7.1
Source Description	The source is defined with the SDEF card as an anisotropic point source. The x-ray beam is further collimated to produce a diverging square field with the use of zero importance surfaces, e.g. collimation surfaces. The spectra are defined at 1 keV bins up until the maximum peak tube potential. The relative intensity at each energy bin is defined using the irradiation event tube potential and characterized HVL to generate an equivalent spectrum. This spectrum defines relative intensity at each energy bin.
Cross Sections	ENDF/B-VII
Transport Parameters	Only photons were transported. The photon physics allowed for the generation of electrons and coherent scattering. The transport cut-off energy for photons is set at 1 keV, after which their energy is locally deposited.
Variance Reduction	No variance reduction was applied in this study.
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 dose-area product meter.
Number of Histories and	The radiation transport was carried out until 7.50×10^7 particle
Statistical Uncertainties	histories were performed or until the computer time exceeded 72 hours. The relative errors in the energy deposition tally was less than 5% for all organs in the x-ray field and within 15% for out-of-field organs.
Data Post-Processing	The energy deposition in the organs of interest was normalized to the F6 tally in the volume of air that represents a dose-area product meter and then multiplied by the clinical dose-area product meter reading at that individual irradiation event, as reported in the logfile.

Table 6.

Cumulative % difference in-field organ dose (morphometry-matched hybrid phantom vs patient-specific phantom) by irradiation event number and FOV (S-small, I-intermediate, and L - large).

Patient #	Event 1 S-FOV	Event 72 S-FOV	Event 1 I-FOV	Event 72 I-FOV	Event 1 L-FOV	Event 72 L-FOV
1	68.17	51.56	59.52	33.81	50.70	37.40
2	18.28	14.19	18.09	14.21	9.18	10.11
3	10.50	19.52	5.98	11.81	5.49	12.02
4	24.93	27.66	22.25	20.62	24.56	10.98
5	62.09	39.80	47.44	32.67	59.31	16.62
6	88.61	20.14	93.75	18.23	66.63	25.86
7	19.71	16.74	19.30	28.03	15.71	19.04
8	56.86	37.62	53.27	24.99	34.49	11.49
9	27.84	24.32	26.15	18.06	18.81	14.17
10	33.41	37.35	28.99	26.64	27.04	9.37
11	34.60	28.21	33.42	15.15	21.86	7.63
12	37.40	29.74	29.50	15.41	36.39	12.74
13	168.70	86.99	55.81	46.70	8.08	21.71
14	110.75	41.99	123.75	14.49	32.54	14.62
15	27.30	16.66	28.86	6.57	16.01	15.33
16	14.77	12.54	13.00	12.73	7.60	5.23
17	27.52	25.05	21.51	19.50	17.40	7.40
18	55.20	29.51	50.90	27.09	30.54	24.54
19	27.80	35.47	30.14	24.45	23.97	16.77
20	26.51	16.90	31.44	25.23	35.83	17.81
21	31.69	30.75	28.06	19.84	27.96	8.88
22	38.25	39.99	34.42	20.63	23.38	7.08
23	45.76	20.56	38.85	17.01	34.17	18.48
24	33.41	39.34	33.08	55.99	30.71	28.63
25	51.90	25.02	43.96	18.89	38.76	9.69
26	44.87	14.82	41.33	20.63	26.45	22.61
27	34.66	17.21	34.80	15.35	34.41	16.19
28	53.95	65.44	49.66	26.86	38.30	12.87
29	46.16	34.78	47.80	23.19	42.18	11.39

Table 7.

Identity of “in-field” organs (highest to lowest dose) for each patient and field size in the parametric study. FOV in units of cm.

Patient	FOV	In-field organs			
1	11.5	Heart	Lung	Spleen	Stomach
	22.9	Spleen	Lung	Kidneys	Heart
	45.9	Kidneys	Spleen	Lung	Pancreas
2	11.5	Heart	Lung	Spleen	Stomach
	22.9	Spleen	Lung	Heart	Stomach
	45.9	Spleen	Kidneys	Lung	Liver
3	11.5	Heart	Lung	Spleen	Stomach
	22.9	Spleen	Lung	Heart	Stomach
	45.9	Spleen	Kidneys	Lung	Liver
4	11.5	Heart	Lung	Spleen	Stomach
	22.9	Spleen	Lung	Heart	Stomach
	45.9	Spleen	Kidneys	Lung	Liver
5	11.5	Spleen	Heart	Lung	Kidneys
	22.9	Spleen	Lung	Heart	Kidneys
	45.9	Spleen	Lung	Kidneys	Pancreas
6	11.5	Heart	Spleen	Lung	Kidneys
	22.9	Spleen	Lung	Heart	Kidneys
	45.9	Spleen	Lung	Kidneys	Pancreas
7	11.5	Heart	Lung	Spleen	Stomach
	22.9	Heart	Spleen	Lung	Stomach
	45.9	Spleen	Lung	Heart	Kidneys
8	11.5	Heart	Lung	Spleen	Stomach
	22.9	Spleen	Lung	Heart	Stomach
	45.9	Spleen	Lung	Kidneys	Heart
9	11.5	Heart	Lung	Spleen	Stomach
	22.9	Spleen	Lung	Heart	Stomach
	45.9	Spleen	Lung	Heart	Kidneys
10	11.5	Heart	Lung	Spleen	Stomach
	22.9	Spleen	Lung	Heart	Stomach
	45.9	Spleen	Lung	Heart	Kidneys

Patient	FOV	In-field organs			
11	22.9	Spleen	Heart	Lung	Stomach
	45.9	Spleen	Lung	Heart	Kidneys
	11.5	Heart	Lung	Spleen	Stomach
12	22.9	Lung	Spleen	Heart	Stomach
	45.9	Spleen	Lung	Heart	Kidneys
	11.5	Heart	Spleen	Lung	Kidneys
13	22.9	Spleen	Lung	Heart	Kidneys
	45.9	Spleen	Lung	Kidneys	Pancreas
	11.5	Lung	Heart	Spleen	Liver
14	22.9	Spleen	Lung	Liver	Pancreas
	45.9	Kidneys	Spleen	Pancreas	Lung
	11.5	Heart	Lung	Spleen	Stomach
15	22.9	Spleen	Lung	Heart	Kidneys
	45.9	Kidneys	Spleen	Lung	Pancreas
	11.5	Heart	Spleen	Lung	Stomach
16	22.9	Spleen	Lung	Heart	Stomach
	45.9	Spleen	Kidneys	Lung	Pancreas
	11.5	Heart	Spleen	Lung	Stomach
17	22.9	Spleen	Lung	Heart	Stomach
	45.9	Spleen	Kidneys	Lung	Pancreas
	11.5	Heart	Spleen	Lung	Stomach
18	22.9	Spleen	Lung	Heart	Stomach
	45.9	Spleen	Kidneys	Lung	Pancreas
	11.5	Heart	Lung	Spleen	Kidneys
19	22.9	Spleen	Lung	Heart	Kidneys
	45.9	Spleen	Kidneys	Lung	Liver
	11.5	Heart	Lung	Spleen	Stomach
20	22.9	Spleen	Lung	Heart	Stomach
	45.9	Spleen	Lung	Kidneys	Heart
	11.5	Heart	Lung	Spleen	Stomach
	22.9	Spleen	Lung	Heart	Kidneys

Patient	FOV	In-field organs			
21	45.9	Spleen	Lung	Kidneys	Heart
	11.5	Heart	Lung	Spleen	Stomach
	22.9	Lung	Spleen	Heart	Kidneys
22	45.9	Spleen	Lung	Kidneys	Heart
	11.5	Spleen	Heart	Lung	Stomach
	22.9	Spleen	Heart	Lung	Stomach
23	45.9	Spleen	Lung	Heart	Liver
	11.5	Spleen	Heart	Lung	Stomach
	22.9	Spleen	Lung	Heart	Stomach
24	45.9	Spleen	Lung	Heart	Stomach
	11.5	Heart	Lung	Spleen	Stomach
	22.9	Spleen	Lung	Heart	Kidneys
25	45.9	Spleen	Lung	Kidneys	Heart
	11.5	Spleen	Heart	Lung	Stomach
	22.9	Spleen	Heart	Lung	Stomach
26	45.9	Spleen	Lung	Heart	Stomach
	11.5	Spleen	Heart	Lung	Stomach
	22.9	Spleen	Heart	Lung	Stomach
27	45.9	Spleen	Lung	Heart	Liver
	11.5	Spleen	Heart	Lung	Stomach
	22.9	Spleen	Heart	Lung	Stomach
28	45.9	Spleen	Lung	Heart	Stomach
	11.5	Spleen	Stomach	Heart	Lung
	22.9	Spleen	Stomach	Heart	Lung
29	45.9	Spleen	Stomach	Lung	Liver
	11.5	Heart	Lung	Spleen	Kidneys
	22.9	Spleen	Lung	Heart	Kidneys
	45.9	Spleen	Lung	Kidneys	Heart

Table 8.

Organ doses (mGy), RMSD (mGy), and percent differences for logfiles #1 to #4 in the clinical procedure study.

Logfile	Phantom	Lung	Heart	Liver	Stomach	RMSD
#1	Matched Hybrid Patient-Specific % <i>diff</i>	4.69	3.56	0.34	0.19	2.95
		4.64	4.25	0.63	0.35	3.17
		1%	16%	46%	46%	7%
#2	Matched Hybrid Patient-Specific % <i>diff</i>	Heart	Spleen	Lung	Pancreas	RMSD
		9.48	4.59	6.66	1.06	6.25
		8.71	7.41	7.4	5.04	7.26
#3	Matched Hybrid Patient-Specific % <i>diff</i>	9%	38%	10%	79%	14%
		Lung	Heart	Liver	Stomach	RMSD
		0.74	0.53	0.19	0.05	0.46
#4	Matched Hybrid Patient-Specific % <i>diff</i>	0.87	0.79	0.53	0.16	0.65
		15%	34%	64%	67%	29%
		Heart	Lung	Liver	Stomach	RMSD
		12.52	10.6	5.32	3.77	8.83
		11.62	9.51	4.05	3.35	7.95
		8%	11%	32%	12%	11%