Size-specific dose estimate (SSDE) provides a simple method to calculate organ dose for pediatric CT examinations

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Purpose: To investigate the correlation of size-specific dose estimate (SSDE) with absorbed organ dose, and to develop a simple methodology for estimating patient organ dose in a pediatric population (5–55 kg).

Methods: Four physical anthropomorphic phantoms representing a range of pediatric body habitus were scanned with metal oxide semiconductor field effect transistor (MOSFET) dosimeters placed at 23 organ locations to determine absolute organ dose. Phantom absolute organ dose was divided by phantom SSDE to determine correlation between organ dose and SSDE. Organ dose correlation factors (CF_{SSDE}^{organ}) were then multiplied by patient-specific SSDE to estimate patient organ dose. The CF_{SSDE}^{organ} were used to retrospectively estimate individual organ doses from 352 chest and 241 abdominopelvic pediatric CT examinations, where mean patient weight was $22 \text{ kg} \pm 15$ (range 5–55 kg), and mean patient age was $6 \text{ yrs} \pm 5$ (range 4 months to 23 yrs). Patient organ dose estimates were compared to published pediatric Monte Carlo study results.

Results: Phantom effective diameters were matched with patient population effective diameters to within 4 cm; thus, showing appropriate scalability of the phantoms across the entire pediatric population in this study. Individual CF_{SSDE}^{organ} were determined for a total of 23 organs in the chest and abdominopelvic region across nine weight subcategories. For organs fully covered by the scan volume, correlation in the chest (average 1.1; range 0.7–1.4) and abdominopelvic region (average 0.9; range 0.7–1.3) was near unity. For organ/tissue that extended beyond the scan volume (i.e., skin, bone marrow, and bone surface), correlation was determined to be poor (average 0.3; range: 0.1–0.4) for both the chest and abdominopelvic regions, respectively. A means to estimate patient organ dose was demonstrated. Calculated patient organ dose, using patient SSDE and CF_{SSDE}^{organ} , was compared to previously published pediatric patient doses that accounted for patient size in their dose calculation, and was found to agree in the chest to better than an average of 5% (27.6/26.2) and in the abdominopelvic region to better than 2% (73.4/75.0).

Conclusions: For organs fully covered within the scan volume, the average correlation of SSDE and organ absolute dose was found to be better than $\pm 10\%$. In addition, this study provides a complete list of organ dose correlation factors (CF_{SSDE}^{organ}) for the chest and abdominopelvic regions, and describes a simple methodology to estimate individual pediatric patient organ dose based on patient SSDE. © 2014 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4884227>]

Key words: CT, SSDE, Pediatrics, radiation dosimetry

1. INTRODUCTION

The use of volume computed tomography (CT) dose index ($CTDI_{vol}$) and dose length product (DLP) has long been understood to be inappropriate for patient dosimetry in CT (Ref. 1). Currently, there are two approaches for estimating patient organ dose in CT: first, an empirical dose measurement using physical anthropomorphic phantoms in conjunction with any number of dosimeter options, one example of which is the use of metal oxide semiconductor field effect transistors (MOSFETs),^{2,3} and second, software dose calculations using computational Monte Carlo phantoms.^{4–7}

The use of Monte Carlo may provide the closest estimate for individualized patient dosimetry, and is generally considered the gold standard among the different dosimetry techniques.^{4,5,7–9} Several research groups are investigating different techniques to improve calculation times for patient-specific Monte Carlo dose estimation;^{10,11} such efforts may provide real-time Monte Carlo based patient dosimetry in the future. However, patient-specific Monte Carlo techniques currently require high computational performance, a highly specialized programming skill set, and is time consuming. For this reason, only a few academic institutions have the means to make these calculations, thus rendering Monte Carlo based

patient dosimetry impractical in a busy clinical atmosphere. A potential alternative to patient-specific Monte Carlo calculations would be to use Monte Carlo precomputed organ dose values from libraries of computational phantoms. The computational phantoms would be matched to patients using effective diameter, weight, or some other metric. Once matched, the already calculated computational phantom organ dose values would act as a surrogate for patient-specific organ dose. Although the computational phantom library approach would be much faster, rendering it feasible for clinical implementation, a potential limitation to this approach would be the lack of flexibility in matching scan acquisition parameters from different CT vendors.

The use of physical anthropomorphic phantoms for organ dosimetry has been shown to be as accurate as Monte Carlo organ dosimetry in one study.⁶ The phantoms allow for a means to perform empirical-based organ dosimetry, and are generally flexible for estimating patient dosimetry across a wide range of scan technique factors in a timely manner. However, physical anthropomorphic phantoms can be very costly and are limited in scope since the phantoms come in discrete sizes.

To be practically implemented, ideal patient-specific dosimetry for CT must be accurate and timely, or will fall short of implementation in clinical practice. Recent studies have investigated the potential correlation between size-specific dose estimates (SSDE) (Ref. 12) and adult organ dosimetry,^{13–15} potentially allowing for both an accurate and timely approach to CT patient dosimetry. In those studies, absorbed doses to a limited number of adult organs in the thorax and abdomen were shown to correlate with calculated patient effective diameters and SSDE. Patient size was shown to have a significant correlation with patient organ dose. The results from these studies demonstrate that the development of a simple approach toward patient-specific CT dosimetry using organ dose estimates may be possible using SSDE.

In this work, the correlation of absolute organ dose with SSDE using a family of physical anthropomorphic phantoms was investigated. Twenty-three different organ or tissue doses were measured for a representative CT pediatric population. Furthermore, we investigated the use of the phantom organ dose correlation factors, in conjunction with patient-specific SSDE, as a means to estimate patient-specific organ dose. This patient organ dosimetry methodology was then retrospectively applied to clinical pediatric patient data (patient population range between 5 and 55 kg). Finally, the resultant patient organ dose estimates were compared with published pediatric organ dose estimates derived using Monte Carlo voxelized phantoms as the gold standard.

2. MATERIALS AND METHODS

To investigate the correlation between organ dose and SSDE, MOSFET (TN-1002RD-H, mobileMOSFET, Best Medical, Canada) dosimeters were used to empirically measure organ dose in the thorax and abdominopelvic regions of four physical anthropomorphic phantoms (ATOM phantom, CIRS, Norfolk, VA).

2.A. MOSFET/MOSFET calibration

Technical descriptions of MOSFET operations were described previously.^{16–18} In order to measure absolute dose in phantoms, 25 MOSFET detectors were calibrated free-in-air for energy dependence with a radiographic x-ray tube.¹⁶ For MOSFET calibration, added aluminum (Al) filtration was placed at the exit port of the x-ray tube to match the CT beam quality; CT beam quality was determined by the half value layer (HVL) at CT isocenter to be 5.67 mm Al for 100 kVp, and 6.93 mm Al for 120 kVp. MOSFET detectors were cross-calibrated using a 0.6 cc ion-chamber detector (10 × 5–0.6, Radcal, Duarte, CA) at both 100 and 120 kVp. MOSFET absolute dose measurement ($D(Q)_{\text{MOSFET}}$) for a specific organ tissue type and beam quality (Q) was calculated using the following equation:

$$D(Q)_{\text{MOSFET}} = \left(\frac{\text{MOSFET}_{\text{reading}}}{\text{CF}_{\text{MOSFET}}} \right) \times \left[\left(\frac{\mu_{\text{en}}}{\rho} \right)_{\text{air}}^w \right]_{\text{tissue}}, \quad (1)$$

where the $\text{MOSFET}_{\text{reading}}$ (mV) was the absorbed dose measurement made in the phantom's various organs, $\text{CF}_{\text{MOSFET}}$ (mV/cGy) was the MOSFET detector dose calibration factor established using the ion chamber, and $[(\mu_{\text{en}}/\rho)_{\text{air}}^w]_{\text{tissue}}$ was the in-air to tissue correction factor derived from AAPM Report 76.¹⁹ Tissue correction factors for soft tissue, muscle, lung, skin, and bone were taken from Table 10 of AAPM Report 76 and interpolated to determine the proper correction factor based on the beam quality of the CT scanner used to scan the phantoms. Breast dose was performed using the soft tissue correction factor since the female pediatric breast is predominantly glandular in nature;²⁰ it is interesting to note that an application of a breast tissue specific correction factor would have altered the dose calculation by only 0.1% (e.g., 0.947 vs 0.944 soft tissue vs breast tissue correction factors for 100 kVp, respectively).

HVL values have been shown to vary by as much as 5 mm Al when measured laterally off isocenter.²¹ It was assumed that potential increases in measurement accuracy that would come from correcting each individual MOSFET reading as a function of their location corresponding to the azimuthal fan beam angle would be negligible since mass energy-attenuation coefficients do not vary widely over the full range of potential HVL values (e.g., soft tissue varies approximately from 0.943 to 0.968 for HVL values of 5–10, respectively).¹⁹

2.B. Physical Anthropomorphic phantoms

Four physical anthropomorphic phantoms, representing a 1-, 5-, 10-year old, and adult female patient were scanned to determine organ dose. The adult female phantom (referred to as the 15-year-old phantom) was used to represent both male and female young adolescent patients. The phantoms consisted of multiple simulated tissue types: lung, breast, soft tissue, brain, sinus, spinal cord, spinal disks, cartilage, and bone. Simulated bone density was developed to be age appropriate, which accounted for the difference of bone marrow

FIG. 1. Physical anthropomorphic phantoms. (a) The 1-, 5-, 10-, and 15-year-old anthropomorphic phantoms are demonstrated. (b) Locations within the phantom's organs were provided allowing for MOSFET organ dosimetry. All locations within each phantom organ were used for dosimetry. A reconstructed CT image of the representative slice is shown.

distribution with age. Tissue types were engineered to produce photon attenuation values within 1% for bone and soft tissue substitute and within 3% for lung tissue substitute over the range of 30–20 000 keV (as stated in the CIRS product literature).

The phantoms were equipped with 5 mm diameter holes placed at organ locations. MOSFET dosimeters were placed in all available holes within each study organ (Fig. 1). A total of 23 organ doses were calculated: thyroid, lungs, breast, esophagus, thymus, heart wall, bone marrow, bone surface, skin, liver, kidneys, gall bladder, pancreas, adrenal gland, spleen, stomach, colon, bladder, intestines, prostate, testes, ovaries, and uterus. These organs were selected to coincide with organs supplied with radiation tissue weighting factors (w_T) as published in Report 103 by the International Commission on Radiological Protection (ICRP).²² MOSFETs were repeatedly placed throughout the phantom volume to cover all organs. The number of data points varied depending on phantom size. The 1-year-old phantom consisted of 444, the 5-year-old phantom consisted of 788, the 10-year-old phantom consisted of 892, and the 15-year-old phantom consisted of 1172 individual measurements over all 23 organ and tissue types measured.

For calculated red bone marrow and bone surface doses to the chest and abdominopelvic regions, MOSFETs were placed within the following bony structures: scapulae, clavicles, sternum, ribs, spine (T1–L5), pelvis, and sacrum. Red marrow absolute dose was calculated using attenuation correcting soft tissue ratio ($[(\mu_{en}/\rho)_{air}^w]_{tissue}$), since red bone marrow coincided with soft tissue within 5% for x-ray energies >30 keV.^{23,24} The absolute dose measured for the red bone marrow was scaled according to the fractional distribution of active marrow at bone sites as proposed by Cristy and Eckerman.²⁵ Bone surface absolute dose was calculated using attenuation correction bone ratio ($[(\mu_{en}/\rho)_{air}^w]_{bone}$). However,

due to the many variables in pediatric bone mineral ratios,²⁶ the bone surface dose in the 1-, 5-, and 10-year-old phantoms was corrected using bone to marrow ratios in the chest and abdominopelvic region calculated from a published study on pediatric bone dose.⁴ The 15-year-old phantom bone surface dose was corrected using adult mineralized bone ratios calculated from ICRP Report 70.²⁷ Skin dose was measured by placing MOSFETs on the surface of the phantoms. Skin absolute dose for the chest and abdominopelvic regions was calculated using attenuation correcting skin ratio ($[(\mu_{en}/\rho)_{air}^w]_{skin}$). By assuming the phantoms were approximately ellipsoid in shape, the total surface area of each phantom was calculated using the Knud Thomsen approximation.²⁸ The surface area ratio of scan area to whole phantom was used to correct the skin dose. Skin, bone marrow, and bone surface values were distributed across both the chest and abdominopelvic regions and they were separately calculated for dose based on the different exposure parameters for the chest and abdominopelvic regions.

No arms were present on the phantoms to simulate arms raised above the head during the CT scan of the trunk.

2.C. Phantom CT scan parameters

All phantom scans were performed helically on a Lightspeed VCT-XTe (GE Healthcare, Waukesha, WI). Each phantom was scanned based on established, unmodified, patient scan protocols. Initially, the phantoms were aligned with laser placement and verified with a scanned projection radiograph (SPR) (e.g., “ScoutTM” scan). From the SPR image, the scan volume for the chest was landmarked from the top of the lung apices to approximately 10 mm below the lung base. The abdominopelvic scans were landmarked from the diaphragm, emulating an end-expiratory breath hold, to the bottom of the ischium. Chest and abdominopelvic scans were performed separately. Each scan was repeated four times to average the effects of dosimetric spatial distribution from helical scanning.

2.D. Organ dose correlation factor with SSDE methodology

An effective diameter was calculated for each of the physical anthropomorphic phantoms using the formulation described in AAPM Report 204:¹²

$$\text{effective diameter} = \sqrt{AP \times LAT}, \quad (2)$$

where anteroposterior (AP) and lateral (LAT) measurements were made, as recommended in AAPM report 204,²⁹ at approximately midway through the phantom chest and abdomen; these measurements typically corresponded to the largest slice in their respective scan regions. In the case of the 15-year-old phantom, two effective diameters were measured in the chest, one male, using an AP measurement from the posterior skin to the anterior surface of the sternum and another female, using an AP measurement from the posterior skin to the maximum anterior measurement of the breast. The phantom effective diameter was then compared to each

weight-based patient population average effective diameter of the chest and abdomen to determine which phantom most closely emulated the given pediatric weight-based population.

To investigate the correlation between organ dose and SSDE the following scaling dose correlation factors (CF_{SSDE}^{organ}) were established for each organ and phantom size:

$$CF_{SSDE}^{\text{organ}} = \frac{D(Q)_{\text{MOSFET}}^{\text{organ}}}{SSDE_{\text{phantom}}}, \quad (3)$$

where $D(Q)_{\text{MOSFET}}^{\text{organ}}$ is the absolute dose measured using equation [Eq. (1)] for the physical anthropomorphic phantom organs and $SSDE_{\text{phantom}}$ is calculated as previously described in AAPM Report 204 using the effective diameter calculated in equation [Eq. (2)] to look up an f-s coefficient conversion factor to scale volume computed tomography dose index ($CTDI_{\text{vol}}$) values calculated using either a 16 or 32 cm diameter CTDI phantom.^{12,29}

$$SSDE_{\text{patient or phantom}} = CTDI_{\text{vol}}^{16 \text{ or } 32} \times f_{\text{size}}^{16 \text{ or } 32}. \quad (4)$$

$CTDI_{\text{vol}}$ values used for the SSDE calculation were obtained from the CT dose report archived with every patient or phantom CT examination.

2.E. Patient organ dose calculation and comparison

In order to compare the proposed patient organ dose calculation methodology in this study with other published pediatric organ dose values, a retrospective analysis was performed for a nine-month-time period (June 2012 through February 2013). Our institutional review board deemed this quality assurance analysis to be exempt from the need to obtain informed consent. All data were managed in compliance with the Health Insurance Portability and Accountability Act. All patient data were anonymized prior to dosimetric analysis. All examinations analyzed in this study were performed with the same Lightspeed VCT-XTe CT scanner used to scan the physical anthropomorphic phantoms. CT scan protocols were selected on the basis of each patient's weight, which was obtained immediately prior to his or her CT examination. The technique factors used in this study had previously been optimized for ASiRTM (GE Health Care, Waukesha, WI). A more detailed description of these technique factors, along with image quality and relative dose reduction analysis, is available.^{30,31}

The correlation factors were used to estimate patient organ dose by scaling $SSDE_{\text{patient}}$ with $SSDE_{\text{phantom}}$, namely, patient organ dose estimates were calculated from the organ dose correlation factor multiplied with patient-specific SSDE:

$$D_{\text{patient}}^{\text{organ}} = CF_{SSDE}^{\text{organ}} \times SSDE_{\text{patient}}. \quad (5)$$

Furthermore, scaling the organ dose correlation factor with SSDE provided factors that allowed the best option for inter-CT scanner model comparison by utilizing the $CTDI_{\text{vol}}$ value embedded in the SSDE value³² [e.g., accounted for differences in scan technique selection such as tube current time product (mAs), tube potential (kVp), bowtie filter, tube cur-

rent modulation (TCM) strengths, and other unique properties specific to different CT models].

The dosimetry methodology proposed in this study, to calculate individualized patient organ dose, was compared with previously published pediatric organ dose tables as developed using Monte Carlo techniques. The study of Li *et al.*⁵ provided organ dose values for a 6-month-old female and 12-year-old male based on voxelized Monte Carlo phantoms. The study of Lee *et al.*⁴ provided correction factors to calculate organ dose for newborn, 1-year-old, 5-year-old, 10-year-old, and 15-year-old male and female patients. Their data were based on work performed using Monte Carlo voxelized computational phantoms. The study of Turner *et al.*⁷ provided an empirically derived equation, based on patient perimeter, for calculating organ dose for seven organs of the abdomen (liver, stomach, adrenals, kidney, pancreas, spleen, gall bladder); the organ dosimetry methodology of Turner *et al.* was based on a combination of size dependent computational phantoms.³³ In order to compare results, since our CT examination data were categorized by patient weight, the average age of our patient weight based categories was calculated and the following weight based chest and abdominopelvic CT scan protocols were compared to the Monte Carlo publications: 0–7.4 kg (7 months $\pm$ 6) data were compared to the newborn data from Lee *et al.* and the 6-month-old data from Li *et al.* The 18.5–22.4 kg (5.4 yrs $\pm$ 1.8) data were compared to the 5-year-old data from Lee *et al.* The 31.5–40.4 kg (10.2 yrs $\pm$ 2.8) data were compared to the 10-year-old data from Lee *et al.* and the 12-year-old data from Li *et al.* The 40.5–55 kg (15.2 yrs $\pm$ 3.9) data were compared to the 15-year-old male and female data from Lee *et al.* The average patient population AP and LAT measurements from our study were used to calculate the patient perimeter that was used to compare the resulting organ dose values from Turner *et al.* The methodology of Turner *et al.* was only directly comparable to the 18.5–22.4 kg (5-year old) and 31.5–40.4 kg (10-year old) CT examinations due to the conditions under which the Turner's methodology could be applied, namely, use of fixed tube current, $CTDI_{\text{vol}}$ computed using 32 cm diameter CTDI phantom, use of adult sized bowtie filter, and the organs must be fully irradiated.⁷ The CT examinations for the 0–7.4 kg (<1-year old) population could not be directly compared since scanner dosimetry was acquired using a 16 cm diameter CTDI phantom, and the 40.5–55 kg population could not be compared since it was scanned using TCM instead of fixed tube current.

Where necessary, the organ dose results from the comparative studies were scaled to match the $CTDI_{\text{vol}}$, kVp, and mAs from our study scan parameters.

2.F. Statistical techniques

All data in this study were summarized using descriptive statistical analysis. Data analysis was calculated using Excel (ver 2010, Microsoft Corp., Redmond, WA). Error bars shown represent one standard deviation from the mean organ dose of each patient weight population from our study's patient cohorts.

TABLE I. Phantom and patient size comparison.

	1 yo Phantom	Patient (0–11.4 kg)	Maximum difference
Effective diameter chest (cm)	13	12–15	2
Effective diameter abdomen (cm)	13	12–16	3
	5 yo Phantom	Patient population (11.5–22.4 kg)	Maximum difference
Effective diameter chest (cm)	15	16–18	3
Effective diameter abdomen (cm)	17	16–18	1
	10 yo Phantom	Patient population (22.5–40.4 kg)	Maximum difference
Effective diameter chest (cm)	19	19–21	3
Effective diameter abdomen (cm)	18	19–22	4
	15 yo Phantom	Patient population (40.5–55 kg)	Maximum difference
Effective diameter chest (M) (cm)	22	24	2
Effective diameter chest (F) (cm)	23	24	1
Effective diameter abdomen (cm)	20	24	4

3. RESULTS

3.A. Patient populations

A total of 593 patient examinations were analyzed for individual organ dose, 352 chest and 241 abdominopelvic. Exam techniques for patients weighing between 5 and 55 kg were analyzed in this study, where the mean patient weight was $22 \text{ kg} \pm 15$ (range 5–55 kg), and the mean patient age was $6 \text{ yrs} \pm 5$ (range 4 months to 23 yrs). Although the majority of examinations analyzed for organ dose were performed in patients in the pediatric age range, some young adults who were being followed for pediatric tumors and whose weight was $\leq 55 \text{ kg}$, also were studied.

3.B. Phantom and patient size analysis

The four phantoms are shown to be scalable with the various patient weight based populations (Table I). The overall difference between the four phantoms and the pediatric pa-

tient population (5–55 kg) investigated in this work was between 1 and 4 cm.

3.C. Organ dose and SSDE correlation factors

Table II shows the CF_{SSDE}^{organ} for the nine chest organs across the nine weight categories. In Table II, the 15-year-old phantom column is separated into two subcolumns, male (M) and female (F), since SSDE is recorded separately based on gender. Table III shows CF_{SSDE}^{organ} for the 17 abdominopelvic organs investigated. The average correlation factors were calculated in the chest (1.1; range 0.7–1.4) and abdominopelvic (0.9; range 0.7–1.3); the average absolute organ dose normalized by SSDE was within $\pm 10\%$ of unity.

3.D. Patient organ dose value comparison

For organ dose values of a chest CT examination, the calculation methodology in this study agreed to better than

TABLE II. Chest correlation factors as derived from equation [Eq. (3)].

	1 yo			5 yo			10 yo		15 yo		
	6–7.4 kg	7.5–9.4 kg	9.5–11.4 kg	11.5–14.4 kg	14.5–18.4 kg	18.5–22.4 kg	22.5–31.4 kg	31.5–40.4 kg	40.5–55 kg		
kVp	100	100	100	100	100	100	100	120	120		
mAs	26	26	30	32	38	40	46	67 ^a	81 ^a		
									M	F	
Average effective diameter (cm)	5.11 ± 1.0	13.5 ± 1.0	14.5 ± 0.5	15.5 ± 0.8	16.7 ± 0.8	17.6 ± 1.3	19.2 ± 1.4	21.1 ± 1.4	24.2 ± 1.6	23.6 ± 1.2	Average
Organ											
Bone surface	0.2	0.2	0.3	0.4	0.4	0.4	0.4	0.4	0.1	0.1	0.3
Breast	0.8	0.8	1.0	1.1	1.3	1.4	1.1	1.2		0.9	1.1
Heart wall	1.1	1.1	1.3	1.3	1.2	1.1	1.2	1.4	0.8	0.8	1.1
Lungs	1.1	1.2	1.4	1.4	1.4	1.2	1.3	1.5	0.9	0.9	1.2
Esophagus	1.0	0.9	1.2	1.3	1.2	1.1	1.0	1.2	0.9	0.9	1.1
Red BM	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.2
Skin	0.3	0.2	0.3	0.3	0.2	0.2	0.4	0.3	0.1	0.1	0.2
Thymus	1.1	1.2	1.4	1.4	1.3	1.2	1.2	1.4	1.0	1.0	1.2
Thyroid	0.7	0.8	1.0	1.1	1.0	0.9	1.4	1.4	1.2	1.2	1.1

^amAs values shown are averages.

TABLE III. Abdominopelvic correlation factors as derived from equation [Eq. (3)].

	1 yo			5 yo			10 yo		15 yo	Average
	11.5–14.4									
	6–7.4 kg	7.5–9.4 kg	9.5–11.4 kg	kg	14.5–18.4 kg	18.5–22.4 kg	22.5–31.4 kg	31.5–40.4 kg	40.5–55 kg	
kVp	100	100	100	100	100	100	100	120	120	
mAs	40	44	54	58	66	70	80	90 ^a	96 ^a	
Average effective diameter (cm)	11.9 ± 1.1	15.4 ± 1.6	15.8 ± 0.6	16.2 ± 0.8	17.1 ± 1.2	18.2 ± 1.2	20 ± 2.0	21.9 ± 1.0	23.7 ± 1.6	
Organ										
Adrenal gland	0.7	0.7	0.9	1.0	1.0	0.8	0.9	1.2	0.5	0.9
Bladder	0.9	0.9	1.0	0.9	0.9	0.8	0.8	0.9	0.8	0.9
Bone marrow	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.2
Bone surface	0.2	0.2	0.2	0.3	0.4	0.3	0.2	0.3	0.2	0.3
Colon	0.9	0.9	1.0	0.9	1.0	0.9	1.0	1.0	0.9	0.9
Gall bladder	1.1	1.1	1.2	1.1	1.2	1.1	1.1	1.2	0.7	1.1
Intestines	0.9	0.9	1.0	0.9	1.0	0.9	1.0	1.0	0.9	0.9
Kidneys	1.0	1.0	1.1	1.0	1.0	1.0	1.0	1.1	0.7	1.0
Liver	1.0	1.0	1.2	1.0	1.1	1.0	1.1	1.3	0.6	1.0
Ovaries ^b	1.0	0.9	1.0	0.9	1.0	0.9	0.8	0.8	0.6	0.9
Pancreas	0.9	0.9	1.0	0.9	1.2	1.0	1.2	1.2	0.7	1.0
Prostate ^c	0.9	1.0	1.0	1.0	1.0	0.9	0.7	1.0	0.8	0.9
Skin	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.2	0.3
Spleen	0.9	1.0	1.1	0.8	1.0	0.8	0.9	1.0	0.5	0.9
Stomach	1.0	0.9	1.0	1.1	1.3	1.0	1.1	1.2	0.7	1.0
Testes ^c	0.8	0.7	0.9	0.9	0.9	0.5	0.7	0.4	1.0	0.8
Uterus ^b	1.0	0.9	1.0	0.9	1.0	0.9	0.8	0.9	0.8	0.9

^amAs values shown are averages taken from the varying mA due to auto exposure correction.

^bOnly included in female total.

^cOnly included in male total.

8% (23.1/21.4), 12% (22.1/25.0), 19% (35.5/29.8), and 16% (29.7/25.5) with Lee *et al.* for the 0-, 5-, 10-, and 15-year-old patient populations, respectively, and to better than 15% (23.1/27.0) and 26% (35.5/28.1) with Li *et al.* for the 0- and 10-year-old patient populations, respectively (Fig. 2), where a simple summation of all pertinent organ dose values was used as a means for comparison.

For a CT examination of the abdominopelvic region, the organ dosimetry methodology in this study agreed to better than 1% (69.7/70.7), 15% (65.1/56.7), 3% (87.4/90.0), and 9% (67.8/62.4) with Lee *et al.* for the 0-, 5-, 10-, and 15-year-old patient populations, respectively (Fig. 3). Generally, the greatest difference was seen in the pelvic region for the male prostate and testes organ doses. For these organs, the data from Lee *et al.* underestimated the absolute organ dose as compared to the work by Li *et al.* and this study. Additionally, the calculation methodology in this study agreed to better than 16% (69.7/82.7) and 0.4% (87.4/87.8) with Li *et al.* for the 0- and 10-year-old abdominopelvic patient populations, respectively. For the study of Turner *et al.*, our calculation methodology agreed to better than 9% (32.8/36.0) and 12% (47.1/41.9) for the 5- and 10-year-old abdominopelvic patient populations, respectively, but deviated by as much as 53% (33.4/71.7) and 55% (28.5/61.9) for the 0- and 15-year-old patient populations, respectively because the scan parameters in this study, for the 0- and 15-year-old patient populations, were

incompatible with the correction factors from Turner *et al.* as previously described.

4. DISCUSSION

The primary goal of this study was to investigate the correlation between organ absolute doses with SSDE. A secondary goal of this study was to develop a simple and straightforward means for estimating pediatric patient organ dose using correlation factors multiplied with patient SSDE.

The correlation factors in both the chest (1.1; range 0.7–1.4) and abdominopelvic region (0.9; range 0.7–1.3) were, on average, near unity for organs fully covered by the scan volume; this demonstrates that SSDE may be used as a good approximation to estimate organ dose values. Correlation factors with values less than unity represent situations when SSDE overestimated organ dose. The average correlation factors for organ/tissue that extended outside of the scan volume (i.e., skin, bone marrow, and bone surface) demonstrate a poor correlation with SSDE; where the average factor was 0.3 (range: 0.1–0.4) for both the chest and abdominopelvic regions; hence, SSDE severely overestimated the actual organ/tissue dose.

The organ dose calculation methodology in this study relies on the use of patient-specific SSDE. Current patient dose calculation methodologies that provide organ correction

FIG. 2. Comparison of chest absolute organ dosimetry. Monte Carlo computerized phantom based pediatric dosimetry studies [Li *et al.* (Ref. 5) and Lee *et al.* (Ref. 4)] were compared with this study. The Monte Carlo study results were corrected to match scan acquisition parameters of this study (i.e., mAs, kVp, and CTDI_{vol}). The Monte Carlo study results were categorized by age as compared to the weight classifications in this study: (a) 0-year old (yo) 0–7.4 kg, (b) 5 yo 18.5–22.4 kg, (c) 10 yo 31.5–40.4 kg, and (d) 15 yo 40.5–55 kg.

factors normalize their results by CTDI_{vol} .³² The variations in radiation output due to the selection of kVp, mAs, filter selection, reconstructed image thickness, and detector binning are accounted for by normalizing patient organ dose by CTDI_{vol} . However, CTDI_{vol} is calculated as an average of all beam current values used to acquire a CT image, and therefore, may be subject to variation where TCM is utilized for image formation. A recent study by Leng *et al.*,³⁴ investigated the variation of SSDE with TCM in the abdomen ($n = 100$ consecutive abdominal CT exams; BMI range from 14.9 to 41.5). They concluded that there was no statistically significant difference when SSDE was calculated using the regional CTDI_{vol} from the abdominal examination or from the average variation in CTDI_{vol} /mAs calculated for every reconstructed CT image, i.e., a “slice-specific” SSDE. TCM is not expected to vary greatly in the abdominopelvic region due to the generally consistent attenuation through the scan volume. A different study by Khatonabadi *et al.*¹³ explored the correlation between patient effective diameter and CTDI_{vol} in the presence of TCM. For the lungs ($n = 32$ patients; range of 23–38 cm effective diameter), they determined that the regional CTDI_{vol} calculated only for chest CT examination correlated well [$R^2 = 0.88$ (F) and 0.83 (M)] with patient effective diame-

ter. This result also held true for their analysis of breast dose from the chest CT examinations ($n = 20$ patients; range of 23–38 cm effective diameter; $R^2 = 0.88$). In summary, they concluded that regional CTDI_{vol} correlated well with patient size and may be sufficient to provide information for organ dose estimation. The results from Khatonabadi *et al.* also demonstrate that CTDI_{vol} itself will not be an adequate normalization factor for organ dose in the presence of varying patient sizes, and that the use of SSDE will be critical as a normalization factor when developing a universally applicable correlation factor for patient-specific organ dose estimation.

When compared with previously published Monte Carlo based pediatric patient dosimetry methodologies, the methodology in this study differed in organ definitions in some cases (i.e., intestines vs small intestine wall, colon vs colon wall, and bladder vs urinary bladder wall). The primary difference between the small intestine and colon is that the organ doses calculated using the physical phantoms model the soft tissue abdominopelvic organs as one material. The organ doses measured for the intestines and colon are measured at spatial reference points corresponding to the average location of those organs; hence, the Monte Carlo methodologies based

FIG. 3. Comparison of abdominopelvic absolute organ dosimetry. Monte Carlo computerized phantom based pediatric dosimetry studies [Li *et al.* (Ref. 5), Lee *et al.* (Ref. 4), and Turner *et al.* (Ref. 7)] were compared with this study. Those results were corrected to match scan acquisition parameters of this study (i.e., mAs, kVp, and CTDI_{vol}). The Monte Carlo study results were categorized by age as compared to the weight classifications in this study: (a) 0 yo 0–7.4 kg, (b) 5 yo 18.5–22.4 kg, (c) 10 yo 31.5–40.4 kg, and (d) 15 yo 40.5–55 kg.

on computational phantoms provide a more realistic modeling of the gastrointestinal tract. Despite these differences, an overall good agreement exists between the intestine and colon doses calculated using this study's methodology compared to the other published Monte Carlo results (average agreement of 15% with a range of 2%–34%).

When compared with the methodology of Lee *et al.*,⁴ their work was simulated for a Siemens 16 slice scanner with contiguous axial imaging while our study acquired data on a GE 64 slice scanner in helical scan mode. Scan landmarks of Lee *et al.* also differed from this study; their study scanned the chest from the clavicles to the middle of the liver which is slightly elongated from the chest scan landmarks of this study and may account for the greater deviation in organ dose values for the 10- and 15-year-old patient populations. The abdominopelvic scan simulated by Lee *et al.* was also slightly elongated to the midfemoral heads.⁴ Also, the study of Lee *et al.*⁴ normalized absolute organ dose to CTDI_{vol} while this study normalized to SSDE. SSDE is more indicative of patient body habitus than CTDI_{vol}. The testes and prostate doses do not match well. They have average percent differences of the order of 361% (2.4/0.5) and 416% (4.4/0.9), respectively; this may be due to the axial image acquisition instead of he-

lical. The clinical protocols modeled in this study are implemented to avoid directly irradiating the testes, however, helical acquisition volume lengths are longer than prescribed due to the necessity of imaging tissue immediately above and below the first and last reconstructed image. This effect, called over-ranging, is necessary to reconstruct these images, but elevates radiation dose to organs immediately outside the scan volume. However, even including the dose deviations of the testes and the prostate, the total percent difference of all organ doses from this study and that of Lee *et al.* was only 2% (73.4/75.0) in the abdominopelvic region and 5% (27.6/26.2) in the chest.

The study of Turner *et al.*⁷ simulated GE, Siemens, Philips, and Toshiba 64 slice CTs over a range of computerized phantom abdominal sizes, and corrected to patient perimeter as a size metric. Of the seven organs that could be compared, this study differed from that of Turner *et al.* by no more than 3% (38.9/40.0) for the 5- (58 cm perimeter) and 10-year-old (70 cm perimeter) patient populations. The methodology proposed by Turner *et al.*⁴ was the first to propose normalizing organ dose correction factors by patient size, but ultimately their methodology was limited in scope (seven organs in the abdomen) and implementation (very

strict conditions under which their methodology could be applied).

In this work, testicular and thyroid organs were not directly covered by the scan volume, but received direct exposure due to over-ranging effects from helical scanning, and also scatter radiation. Due to the variation of over-ranging irradiation, the correlation factor variance was much greater across pediatric weight categories than other directly irradiated organs; thyroid variance was 0.5, compared to the average variance of 0.4, in the chest region, and testicular variance was 0.4, compared to the average variance of 0.2, in the abdominopelvic region for organs fully covered within the scan volume.

Efforts to standardize and potentially automate the calculation of SSDE for each patient CT scan are being investigated through the efforts of an AAPM Task Group 220 (Determination of a Patient Size Metric for CT Size Specific Dose Estimation), the follow-up to Report 204. The hope is that CT manufacturers will implement the routine calculation of SSDE for each scan, much like the current implementation of $CTDI_{vol}$ thus potentially facilitating seamless patient organ dosimetry.

There are several limitations of this study. First, the organ dose calculation methodology assumes that the scan volume fully covers the organ, and thus partially irradiated organs, such as the liver during a chest CT scan, are not included in the overall chest radiation dose calculation. Turner *et al.*⁷ investigated partial organ volume irradiation and concluded that there was a poor correlation between patient size and partial organ dose irradiation. Therefore, to include partially irradiated organs into the organ dose equation, an additional correction factor other than patient size (i.e., SSDE) may be required; further investigation into this area is required. Until partially irradiated organ dosimetry can be included into the overall dose calculation, those dose values calculated in this, and other similar works, will underestimate the actual radiation burden for a particular CT scan. Second, explicitly assumed in this study is that each organ dose is homogenous throughout the entire organ. In actuality, due to the morphology of the human form and the helical nature of a CT scan, organ dose is heterogeneous, especially in large organs such as the liver or lungs that span a large volume of the body.³⁵ Finally, the methodology of this study does not account for dose from scatter in organs outside the scan area (i.e., dose to upper abdominal organs during a chest scan) because the MOSFETs will not provide appropriate measurement precision for CT organ dosimetry calculations when not directly irradiated.

5. CONCLUSION

The results from this study suggest that SSDE is a good surrogate for pediatric organ dosimetry. For organs fully covered within the scan volume, the average correlation of SSDE and organ absolute dose was found to be better than $\pm 10\%$. In addition, we demonstrate a methodology to estimate pediatric patient organ doses based on a simple lookup table of correlation factors that has been shown to be comparable

to more sophisticated Monte Carlo based pediatric dosimetry techniques. Using the methodology proposed in this study, one can use the correlation factors provided in tabular form to facilitate a simple means for pediatric patient specific organ dose calculations taking into account individual patient SSDE.

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