The feasibility of a regional CTDI_{vol} to estimate organ dose from tube current modulated CT exams

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(Received 14 January 2013; revised 26 February 2013; accepted for publication 14 March 2013;
published 5 April 2013)

Purpose: In AAPM Task Group 204, the size-specific dose estimate (SSDE) was developed by providing size adjustment factors which are applied to the Computed Tomography (CT) standardized dose metric, CTDI_{vol} . However, that work focused on fixed tube current scans and did not specifically address tube current modulation (TCM) scans, which are currently the majority of clinical scans performed. The purpose of this study was to extend the SSDE concept to account for TCM by investigating the feasibility of using anatomic and organ specific regions of scanner output to improve accuracy of dose estimates.

Methods: Thirty-nine adult abdomen/pelvis and 32 chest scans from clinically indicated CT exams acquired on a multidetector CT using TCM were obtained with Institutional Review Board approval for generating voxelized models. Along with image data, raw projection data were obtained to extract TCM functions for use in Monte Carlo simulations. Patient size was calculated using the effective diameter described in TG 204. In addition, the scanner-reported CTDI_{vol} ($\text{CTDI}_{\text{vol,global}}$) was obtained for each patient, which is based on the average tube current across the entire scan. For the abdomen/pelvis scans, liver, spleen, and kidneys were manually segmented from the patient datasets; for the chest scans, lungs and for female models only, glandular breast tissue were segmented. For each patient organ doses were estimated using Monte Carlo Methods. To investigate the utility of regional measures of scanner output, regional and organ anatomic boundaries were identified from image data and used to calculate regional and organ-specific average tube current values. From these regional and organ-specific averages, CTDI_{vol} values, referred to as regional and organ-specific CTDI_{vol} , were calculated for each patient. Using an approach similar to TG 204, all CTDI_{vol} values were used to normalize simulated organ doses; and the ability of each normalized dose to correlate with patient size was investigated.

Results: For all five organs, the correlations with patient size increased when organ doses were normalized by regional and organ-specific CTDI_{vol} values. For example, when estimating dose to the liver, $\text{CTDI}_{\text{vol,global}}$ yielded a R^2 value of 0.26, which improved to 0.77 and 0.86, when using the regional and organ-specific CTDI_{vol} for abdomen and liver, respectively. For breast dose, the global CTDI_{vol} yielded a R^2 value of 0.08, which improved to 0.58 and 0.83, when using the regional and organ-specific CTDI_{vol} for chest and breasts, respectively. The R^2 values also increased once the thoracic models were separated for the analysis into females and males, indicating differences between genders in this region not explained by a simple measure of effective diameter.

Conclusions: This work demonstrated the utility of regional and organ-specific CTDI_{vol} as normalization factors when using TCM. It was demonstrated that $\text{CTDI}_{\text{vol,global}}$ is not an effective normalization factor in TCM exams where attenuation (and therefore tube current) varies considerably throughout the scan, such as abdomen/pelvis and even thorax. These exams can be more accurately assessed for dose using regional CTDI_{vol} descriptors that account for local variations in scanner output present when TCM is employed. © 2013 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4798561>]

Key words: CT, CTDI_{vol} , regional CTDI_{vol} , tube current modulation, radiation dose, organ dose, Monte Carlo dose simulations

I. INTRODUCTION

The population radiation exposure due to CT examinations has increased over several decades and as a result agencies such as Food and Drug Administration, International Atomic Energy Agency, American College of Radiology, National Institutes of Health, and Image Gently recommend reporting radiation dose from CT exams.^{1–5} In addition, the State of California mandates health facilities to record dose from CT exams under Assembly Bill No. 510.⁶ Currently, the only values that can easily be calculated and reported, are CTDI_{vol} and DLP, even though neither represents patient dose nor takes into account patient specific factors such as size.⁷

Recently, AAPM Task Group 204 (Ref. 8) described the size specific dose estimate (SSDE), which accounts for patient size by providing conversion factors. These conversion factors vary by patient effective diameter and convert CTDI_{vol} to the SSDE, which is the dose in the middle of the scan volume. These conversion factors were generated from fixed tube current measurements and Monte Carlo simulations and therefore did not specifically address scans performed with tube current modulation (TCM), which is the dominant mode of scanning in today's clinical practice.

The computed tomography dose index (CTDI) was introduced over three decades ago as an index of scanner radiation dose^{9,10} and has been adapted to measurements in a 100 mm ionization chamber (CTDI₁₀₀) and to helical scanning (CTDI_{vol}) in cylindrical plastic phantoms. Despite its limitations in keeping up with new technologies, it is widely used for quality assurance, accreditation, and dose monitoring.^{11,12}

TCM techniques were introduced over a decade ago and since then most clinical protocols have implemented this feature to reduce patient dose while maintaining acceptable image quality.^{13–16} TCM algorithms perform differently across different CT scanner manufacturers but the basic principle is the modulation of the tube current in x-y-z directions. In most

scanners, the x-y or angular modulation adjusts the tube current based on the projection's path length through the object, while the z-axis modulation adjusts the tube current for different attenuations along the scan length.^{17,18}

With the advent of TCM, CTDI_{vol} has again been adjusted. The International Electrotechnical Commission (IEC) has defined CTDI_{vol} for a tube current modulated exam [in the standard 60601-2-44 Amd.1 Ed.3 of IEC (Ref. 19)] as the CTDI_{vol} based on a single average tube current value of the entire scan. While the original definition of CTDI_{vol} assumed a constant tube current (and therefore technically cannot be defined for a variable tube current scan), this practical definition is now adopted and is the method by which CTDI_{vol} is being reported on scans performed with TCM in current clinical practice (e.g., the dose reports provided by scanners).

This leads to the situation depicted in Fig. 1, where a TCM scan is performed and the actual tube current varies significantly throughout the scan, yet only a single value of CTDI_{vol} is reported based on the average value of the tube current across the entire scan. Figure 1(a) depicts the actual tube current value as a function of table position for a chest exam and Fig. 1(b) depicts the same information for an abdomen/pelvis scan. These figures show the significant variation in tube current that occurs as the scan proceeds across areas of varying attenuation characteristics, which result in the (appropriate) variations in tube output milliamperage along the longitudinal direction. In each figure, the dashed line shows the average tube current throughout the entire scan which is the value upon which the scanner reported CTDI_{vol} is based.

There have been several previous efforts to estimate dose to patients under TCM conditions.^{18,20} One of these efforts, Schlattl *et al.*,^{21,22} published dose conversion coefficients for seven voxelized models (baby, child, Jo, RCP-AM, RCP-AF, Irene, and Donna) using idealized TCM profiles based on Gies²³ and Kalender *et al.*¹⁶ Even though the fundamental concepts of TCM are uniform across all CT manufacturers, they tend to differ in implementation and

FIG. 1. (a) An example of a chest exam's TCM profile, illustrating the variation of tube current along patient's z-axis and within the axial plane (the high frequency component). (b) An example of an abdomen/pelvis exam's TCM profile, illustrating three different attenuating regions: lungs, abdomen, and pelvis. CTDI_{vol} reported by the scanner is based on the global average tube current (dashed line).

optimization variable and are not the same as the idealized TCM described by Gies²³ and Kalender.¹⁶ Besides not representing any manufacturer-specific TCM algorithm, the work of Schlattl^{21,22} did not use any quantitative size metric to categorize its patient models.

In this paper, we investigate an adaptation of the TG 204 approach that takes into account the effects of varying tube current in TCM scans. To do this, we will evaluate the scanner-reported global CTDI_{vol} as a predictor of organ dose in a TCM setting and compare against more local versions of scanner output (regional and organ-specific CTDI_{vol}) as a predictor for organ dose. The utility of regional and organ-specific CTDI_{vol} as normalization factors in tube current modulated scans will be explored using Monte Carlo simulations of tube current modulated chest and abdomen/pelvis exams.

II. MATERIALS AND METHODS

II.A. Monte Carlo simulation code

A previously developed and validated Monte Carlo based CT dosimetry package was employed to estimate organ doses from tube current modulated chest and abdomen/pelvis CT exams.^{24–27} A modified source code of MCNPX (Monte Carlo N-Particle eXtended v2.6.0), a radiation transport code developed at Los Alamos National Laboratory, was used for the simulations.^{28,29} All simulations were performed in photon transport mode with a low-energy cutoff of 1 keV. The photon transport mode only tracks photon interactions and assumes secondary electrons deposit their energy at the photon interaction site. This assumption meets with the condition of charged particle equilibrium (CPE), under which kerma can be assumed to be equal to absorbed dose.

II.A.1. MDCT source model

A multidetector row CT (MDCT) scanner (Sensation 64, Siemens Healthcare, Forchheim, Germany) was modeled in the Monte Carlo simulations. The default MCNPX particle source code was modified to model the scanner. The CT x-ray source was modeled by simulating a helical source path while using a point source to emit photons whose initial position and direction were randomly selected based on scanner geometry variables such as source-to-isocenter distance and fan angle. The bowtie filter was modeled by varying the statistical weight of each simulated photon.^{24–26} The approach described by Turner *et al.*²⁷ was used to generate scanner-specific spectrum and filtration description to model the scanner. The scanner model was validated by simulating CTDI₁₀₀ at the center and periphery of both 32 and 16 cm CTDI phantoms and comparing simulated values to physical measurements. Simulation results across all tested conditions agreed with measurements to within 3.7%.²⁷

II.A.2. Voxelized patient models used in Monte Carlo

Voxelized patient models originating from actual CT scans were used in the Monte Carlo simulations. Thirty-nine abdomen/pelvis CT scans acquired on a Siemens Sensation 64

with CareDose 4D, 120 kVp, 275 quality reference mAs, 32×0.6 collimation, pitch of 1, and reconstructed image thickness of 3 mm, were used to generate voxelized abdomen/pelvis models. Similarly, 32 chest CT scans (20 females and 12 males) with 230–250 quality reference mAs were utilized to create voxelized models of chest. To ensure all anatomy was included, all images were reconstructed with a full 500 mm display field of view.

In the abdomen/pelvis models, liver, spleen, and kidneys were contoured and segmented while in the chest models lungs and glandular breast tissue were contoured (the latter was only segmented in female models). Segmented organs were assigned to the corresponding organ using material composition and densities defined by ICRU Report 44.³⁰ Each voxel outside the segmented region was identified as one of the six tissue types (air, water, lung, fat, muscle, and bone) and subdivided into 17 different tissue density levels as a function of voxel CT number.^{18,31,32}

II.A.3. Monte Carlo TCM model

For each patient model, TCM data were extracted from the raw projection data and were modeled in Monte Carlo using the method described by Angel *et al.*¹⁸ TCM data consist of three variables: tube current I , table location z , and tube angle Θ . The tube current value I is a function of table position z and tube angle Θ , $I(z, \Theta)$. For a given patient, all tube current values, $I(z, \Theta)$, were normalized to the maximum tube current value. The normalized tube current data are used in the Monte Carlo simulations as source weights for simulated photons sampled from the table location and tube angle data.

II.B. Simulated CT exams

For each voxelized model, Monte Carlo simulations were performed utilizing each patient's actual TCM information extracted from the raw projection data. The simulated exam lengths were also extracted from the raw projection data, including the z -axis over-ranging. However, due to the voxelized models entirely originating from image data none of the voxelized models include the image data corresponding to the over-ranging region.³³ As a result, the simulated organ doses may slightly underestimate actual dose since there is no dose contribution due to scatter from the over-ranging region; this is assumed to be an insignificant contribution for the organs of interest in this study as they are bigger organs and are not adjacent to the boundaries of the scan region.

II.C. Dose calculations

For each patient model, absorbed dose was calculated for all identified organs. Organ doses were calculated using collision kerma, which is equal to absorbed dose under the assumption of charge particle equilibrium. For each simulated photon, MCNPX tally type *F4 was used to track energy fluence in organs of interest and multiplied by mass energy-absorption coefficients (μ_{en}/ρ) to convert to collision kerma. The resulting dose per simulated photon for each organ was

converted to dose per tube current (mA) by multiplying the Monte Carlo output by a normalization factor, which is scanner, collimation, and kVp dependent and is used to take into account the fluence changes from varying the beam collimation. Absolute organ doses were obtained by multiplying dose per mAs (tube current times rotation time) by the product of maximum tube current value obtained from each patient's TCM data, the exam's number of rotations, and rotation time.¹⁸

II.D. Regional and organ-specific CTDI_{vol}

In addition to recording the scanner-reported CTDI_{vol,global}, regional and organ-specific CTDI_{vol} values were calculated from patient's image data using a MATLAB (Mathworks, Natick, MA) routine. Regional and organ-specific CTDI_{vol} values and the global CTDI_{vol} were used as normalization factors and compared to each other. An exponential relationship between normalized organ dose and effective diameter, similar to the one used in TG 204, was used to assess each CTDI_{vol} as a normalization quantity, as shown in Eq. (1)

$$\begin{aligned} \text{Normalized organ dose} &= \frac{\text{Organ dose}}{\text{CTDI}_{\text{vol}}} \\ &= A \times e^{-B \times \text{Effective diameter}} \end{aligned} \quad (1)$$

where A and B are organ-specific constants.

For the abdomen/pelvis exams, a regional CTDI_{vol} was calculated based on the average tube current value for the abdomen section, defined as the top of liver to the iliac crest, of the original exam along with three organ-specific CTDI_{vol} (Fig. 2). Using a MATLAB function, tube current values and corresponding slice locations were extracted for each patient model. Images containing the abdomen region were manually identified using the starting and ending image numbers as inputs to the function to calculate an average tube current value

FIG. 2. An example of an abdomen/pelvis exam's TCM profile, illustrating three different attenuating regions: lungs, abdomen, and pelvis. The horizontal dashed line through all three regions represents the average tube current over the entire scan length (i.e., global average tube current). The horizontal line at each section represents the average tube current over that specific section.

FIG. 3. An example of a chest exam's TCM profile, illustrating three different attenuating regions: shoulder, low-attenuation region (encompasses most of the lungs, excluding shoulders, scapula, and abdomen). The horizontal dashed line through all three regions represents the average tube current over the entire scan length. The horizontal line at each section represents the average tube current over that specific section.

between those images. Similarly, image numbers of images containing liver, kidneys, and spleen were identified to calculate an average tube current (I) value for each organ. Based on these average tube current values, as shown in Eq. (2), new CTDI_{vol} values were calculated and named: CTDI_{vol,Abd}, CTDI_{vol,Liver}, CTDI_{vol,Spleen}, and CTDI_{vol,Kidneys}

$$\text{CTDI}_{\text{vol,Regional}} = \text{CTDI}_{\text{vol,Global}} \times \frac{I_{\text{Regional}}}{I_{\text{Global}}} \quad (2)$$

Similarly for the chest exams a regional CTDI_{vol}, CTDI_{vol,LowAtt}, defined as the region between the inferior edge of the scapula and superior boundary of the liver, which included most of the lungs but excluded shoulder and any abdominal organs, along with two organ-specific CTDI_{vol} values (CTDI_{vol,Lungs} and CTDI_{vol,Breasts}) were calculated and used as normalization factors (Fig. 3). Table I summarizes different CTDI_{vol} values and their abbreviations.

II.E. Size metric

The equivalent diameter as described in AAPM Task Group 204 report was used as the reference size metric, shown in Eq. (1), to assess the performance of different CTDI_{vol} values as normalization quantities.

Using the definition from TG 204 report, equivalent diameters were calculated for each patient using a set of lateral and anterior-posterior (AP) measurements performed on each axial CT image. Using these measurements, for each image an effective diameter was calculated. For each patient, a single averaged effective diameter was reported and used to investigate correlation with normalized organ doses.

II.F. Statistical analysis

Linear regressions were used to assess the effect of patient size on absolute organ doses and CTDI_{vol}. A scatter

TABLE I. Tabular description and abbreviation of different CTDI_{vol} values.

Exam	Regional		Organ-specific	
	Definition	Abbreviation	Definition	Abbreviation
Abdomen	Top of liver to the iliac crest	CTDI _{vol,Abd}	Images containing liver	CTDI _{vol,Liver}
			Images containing spleen	CTDI _{vol,Spleen}
			Images containing kidneys	CTDI _{vol,Kidneys}
			Images containing lungs	CTDI _{vol,Lungs}
Chest	Inferior edge of the scapula and superior boundary of the liver	CTDI _{vol,LowAtt}	Images containing breasts	CTDI _{vol,Breasts}

diagram with a linear fitted line is shown to demonstrate the relationship between the dose (absolute organ dose and scanner-reported CTDI_{vol}) and patient effective diameters. The coefficient of determination (R^2) was reported to quantify the proportion of variation explained by the effective diameter.

For normalized organ doses, the log-transformation of normalized organ dose is used to fit a linear regression with the covariate of effective diameter using each CTDI_{vol} value (global, regional, and organ-specific) in turn. The coefficient of determination from the linear regression was reported to evaluate the benefit of using each normalized CTDI_{vol} value. A scatter diagram with a fitted exponential curve, as described by Eq. (1), is shown (using original, nonlog-transformed data) to demonstrate the relationship between the normalized organ dose and patient effective diameter for each organ. Pearson's correlations and 95% confidence interval were reported from the log-transformed linear regression. The 95% confidence intervals of regional and organ-specific normalized dose were compared with global normalized dose. A p -value smaller than 0.05 was considered to be significant. All data were analyzed using Stata 12.0 (StataCorp, College Station, TX).

III. RESULTS

III.A. Abdomen/pelvis models

Figure 4(a) shows the absolute value of kidney doses estimated from Monte Carlo simulations plotted as a function of the average effective diameter over the entire scan length. Figures 4(b)–4(d) show the scanner reported CTDI_{vol,global}, CTDI_{vol,Abd}, and CTDI_{vol,Kidneys}, respectively, also plotted as a function of average effective diameter. Each figure also reports the correlation between absolute dose and average effective diameter. These figures show that, as expected in tube current modulated exams, smaller patients receive lower dose, whereas larger patients receive somewhat higher dose. Similar behaviors were observed for liver, spleen, and their CTDI_{vol} values.

Figure 5 shows kidney doses normalized by global, regional, and organ-specific CTDI_{vol} metrics. Figure 5(a) shows kidney doses normalized by global CTDI_{vol,global} as well as the associated correlation between the normalized organ dose

and patient size. Figure 5(b) shows kidney doses normalized by regional and organ-specific CTDI_{vol} (CTDI_{vol,Abd} and CTDI_{vol,Kidneys}) as well as the associated correlations between the normalized organ dose and patient size. The increasing R^2 shows the benefit of using regional and organ-specific CTDI_{vol} normalized dose over global CTDI_{vol} value. For example, using the same effective diameter only 7% of the variation of normalized kidney dose can be explained by CTDI_{vol,global}, whereas 56% and 79% of the variation can be explained when using the regional and organ-specific CTDI_{vol} as normalization quantities. Similar behaviors were observed for liver and spleen. Table II summarizes the results for all three abdominal organs.

Overall the results demonstrate that the regional and organ-specific CTDI_{vol} values yield greater correlations with effective diameter compared to those of CTDI_{vol,global}. Additionally for all three abdominal organs correlations of regional and organ-specific CTDI_{vol} with the effective diameter were significantly greater than the correlation of CTDI_{vol,global} with the effective diameter, whereas the correlations between regional and organ-specific CTDI_{vol} were not statistically different (Table II). Among abdominal organs, spleen showed the poorest correlations with size, while the best correlations were observed for liver. When comparing correlations, CTDI_{vol,liver} and CTDI_{vol,kidney} (organ-specific CTDI_{vol}) performed as better normalization quantities than CTDI_{vol,Abd} (regional CTDI_{vol}). For spleen both regional and organ-specific CTDI_{vol} performed equally.

III.B. Chest models

Figures 6 and 7 summarize the breast dose results obtained for the female chest models. In Figs. 6(a)–6(d), absolute organ doses, CTDI_{vol}, regional CTDI_{vol} (CTDI_{vol,LowAtt}), and organ-specific CTDI_{vol} (CTDI_{vol,Breasts}) illustrate a similar relationship with effective diameter as observed for abdominal organs (as shown in Fig. 4 for kidneys). Similar behaviors were observed for absolute lung dose and CTDI_{vol} values.

Similar to the abdomen/pelvis cases, regional and organ-specific CTDI_{vol} explained more of the variation with effective diameter than CTDI_{vol,global} (Fig. 7). Especially for breasts, which only occupies a portion of the chest region, organ-specific CTDI_{vol} appears to be a more appropriate normalization quantity (58% and 83% by regional and

(a) Absolute Kidney Dose

R-squared = 0.65

(b) CTDI_{vol}

R-squared = 0.72

CTDI_{vol,Abd}

R-squared = 0.83

CTDI_{vol,Kidneys}

R-squared = 0.89

FIG. 4. Absolute Monte Carlo simulated kidney doses (mGy) versus effective diameter (a) and CTDI_{vol} values versus effective diameter (b)–(d). In this small dataset with a small range of different sizes, TCM mode appears to result in lower doses for smaller patients and higher doses for larger patients.

(a) Kidney Dose Normalized by Global CTDI_{vol}

R-squared = 0.07

(b) Kidney Dose Normalized by Reg. and organ-specific CTDI_{vol}

R-squared (regional) = 0.56 R-squared (organ) = 0.79

FIG. 5. For kidneys, (b) normalized dose by regional and organ-specific CTDI_{vol} show a higher correlation with size compared to (a) global CTDI_{vol}. Similar improvements were seen for liver.

TABLE II. R^2 , Pearson correlation, and 95% confidence interval of normalized dose and effective diameter.^a

Model	Organ	n	Global CTDI _{vol}		Regional CTDI _{vol}		Organ-Specific CTDI _{vol}	
			r (95% CI)	R ²	r (95% CI)	R ²	r (95% CI)	R ²
Abd/pel	Liver	39	−0.5108 (−0.712, −0.233)	0.26	−0.8769 ^b (−0.934, −0.776)	0.77	−0.9269 ^b (−0.961, −0.864)	0.86
	Spleen	39	−0.0225 (−0.336, 0.295)	0.0005	−0.6935 ^b (−0.828, −0.484)	0.48	−0.6761 ^b (−0.817, −0.458)	0.46
	Kidney	39	−0.2730 (−0.542, 0.047)	0.07	−0.7510 ^b (−0.862, −0.571)	0.56	−0.8897 ^b (−0.941, −0.798)	0.79

^aLog transformation is applied for Pearson correlation and 95% confidence interval.
^bStatistically significant improvement (p -value < 0.05) compared to global CTDI_{vol} by using log transformation.

organ-specific, but only 8% by CTDI_{vol,global}); whereas for lungs both regional and organ-specific CTDI_{vol} perform equally. For lungs, there was no statistically significant difference between any of the normalization quantities (Table III); this may be expected because lungs occupy most of the thoracic scan length.

FIG. 6. Absolute Monte Carlo simulated breast dose (mGy) versus effective diameter (a) and CTDI_{vol} values versus effective diameter (b)–(d). Similar to the abdominal organs and abdomen/pelvis CTDI_{vol} values, for this small number of patients TCM appears to result in lower doses for smaller and higher doses for larger patients.

(a) Breast Dose Normalized by Global CTDI_{vol}

R-squared = 0.08

(b) Breast Dose Normalized by Reg. and organ-specific CTDI_{vol}

R-squared (regional) = 0.58

R-squared (organ) = 0.83

FIG. 7. For breasts, (b) normalized organ dose by regional and organ-specific CTDI_{vol} show a higher correlation with patient size than (a) global CTDI_{vol}.

IV. DISCUSSION AND CONCLUSION

When TCM scanning methods are used, the global CTDI_{vol} reported by the scanner may not adequately represent the wide range of tube current variations observed in different attenuating regions. Therefore, more regional descriptions of scanner output may be required to represent the different output conditions encountered within the scan. Similarly, a single CTDI_{vol} may not be adequate as a quantity for normalizing out differences in scan parameters and patient size in tube current modulated scans due to different regions within the same scan being subject to different attenuation properties and hence different tube output. A more locally based average tube current/CTDI_{vol}, which only encompasses sections of similar attenuating regions, can more accurately assess TCM scans.

This study showed the feasibility of using regional CTDI_{vol} values to normalize out differences in scan parameters in TCM mode. For all three abdominal organs, the correlations with patient size improved when organ doses were normalized by regional and organ-specific CTDI_{vol} values. This improvement was specifically more satisfactory for liver and kidneys compared to spleen. Normalized spleen dose by regional and organ-specific CTDI_{vol} improved the R² value from 0% correlation to about 50% correlation with size, whereas for liver

and kidneys the improved R² was as high as almost 80%. One possible explanation is the small number of patient models used in this study.

Similar to the abdomen/pelvis models, normalized breast dose by regional and organ-specific CTDI_{vol} in the female thoracic models resulted in higher correlations with patient size compared to the global CTDI_{vol}. In lungs, however, the improvement of R² was not statistically significant once lung dose was normalized by regional and organ-specific CTDI_{vol}. Most of the thorax consists of lungs and therefore regional and lung-specific average tube current values are very close to the global average tube current value; hence, an insignificant improvement was to be expected. Additionally, the lung dataset consisted of both females and males and this was suspected to further have impacted the correlations because there are differences in anatomy between females and males in the thoracic region. To further investigate this hypothesis, a gender-specific analysis was performed.

A separate analysis focusing on each gender individually showed improved R² for normalization by regional and organ-specific CTDI_{vol} for both genders. Table IV and Figs. 8 and 9 illustrate the results of the gender-specific analysis. Looking at absolute lung doses for females and males [Fig. 8(a)], it was determined that females receive higher lung dose compared to males, which could be due to their different shape

TABLE III. R², Pearson correlation, and 95% confidence interval of normalized dose and effective diameter.^a

Model	Organ	n	Global CTDI _{vol}		Regional CTDI _{vol}		Organ-specific CTDI _{vol}	
			r (95% CI)	R ²	r (95% CI)	R ²	r (95% CI)	R ²
Chest	Breasts	20	-0.2835 (-0.645, 0.182)	0.08	-0.7620 (-0.901, -0.482)	0.58	-0.9130 ^b (-0.965, -0.789)	0.83
	Lungs	32	-0.6824 (-0.833, -0.438)	0.47	-0.7474 (-0.869, -0.539)	0.56	-0.7384 (-0.865, -0.525)	0.55

^aLog transformation is applied for Pearson correlation and 95% confidence interval.^bStatistically significant improvement (*p*-value < 0.05) compared to global CTDI_{vol} by using log transformation.

TABLE IV. R^2 , Pearson correlation, and 95% confidence interval of normalized dose and effective diameter.^a

Model	Organ	n	Global CTDI _{vol}		Regional CTDI _{vol}		Organ-specific CTDI _{vol}	
			r (95% CI)	R ²	r (95% CI)	R ²	r (95% CI)	R ²
Chest	Lungs – female	20	–0.7228 (–0.883, –0.412)	0.54	–0.8399 (–0.935, –0.632)	0.71	–0.7447 ^b (–0.893, –0.451)	0.55
	Lungs – male	12	–0.9716 (–0.992, –0.899)	0.92	–0.9650 (–0.990, –0.877)	0.93	–0.9254 ^b (–0.979, –0.750)	0.86

^aLog transformation is applied for Pearson correlation and 95% confidence interval.
^bStatistically significant improvement (p -value < 0.05) compared to global CTDI_{vol} by using log transformation.

in the thoracic region caused by lateral location of glandular breast tissue. However, this difference between females and males was not apparent in the scanner-reported CTDI_{vol} values for these patients [Fig. 8(b)], indicating once again limitations of using CTDI. Table IV summarizes the R^2 , Pearson correlation, and 95% confidence interval between normalized dose and effective diameter, by using log linear regression. Even though the R^2 values increased [Figs. 9(a)–9(c)] when the analysis is separated into females and males, the improvements are not statistically significant. Similar gender-specific analysis was performed on abdomen/pelvis models to investigate whether similar gender-specific behavior is evident, but no difference was observed between females and males in the abdomen [Fig. 9(d)].

The size metric used in this study was the effective diameter as defined by AAPM Task Group 204. The correlation between effective diameter and normalized organ doses was as high as 83% for breasts and 86% for liver. However, this size metric is entirely based on the patient morphology (lateral and AP dimensions) and does not take into account any attenuation properties. This is especially crucial in the thorax due to low attenuating lungs, which make up most of the thorax. Future studies will explore correlations between normalized

dose and attenuation-based size metric such as water equivalent diameter.^{34–37} Additionally, a more locally based size metric, such as an average water equivalent diameter corresponding to the same portion as the regional or organ-specific CTDI_{vol} used for normalization may be a better size indicator. In future studies, a sensitivity analysis will be conducted to determine the most appropriate way to report one size metric per patient.

Another limitation of this study is the limited range of patient sizes and number of patients investigated. Future studies will include a variety of sizes including pediatric and obese patients, to allow for extending the exponential curves to both extremes.

In this study, regional and organ-specific tube current data were calculated based on the anatomic ranges (both regional and organ-specific) extracted for each patient manually, which is not practical to do on a large scale. However, different regions might be identified from the topogram/scout of the patient or from the image data itself. As we have shown in this study regional CTDI_{vol} may yield acceptable results and provide a good alternative to organ-specific CTDI_{vol} and therefore, even a regional identification may be sufficient to provide information for organ dose estimates. If that is the

FIG. 8. Gender-specific analysis performed on the lung data. Absolute lung doses (a) and CTDI_{vol} (b) values are separated into females and males and illustrated versus effective diameter. A visible separation between females and males is demonstrated by the absolute lung doses; however, CTDI_{vol} values do not depict a similar conclusion.

(a) Lung Dose Normalized by Global CTDI_{vol}

R-squared (Female) = 0.54

R-Squared (Male) = 0.92

(b) Lung Dose Normalized by Regional CTDI_{vol}

R-squared (Female) = 0.71

R-Squared (Male) = 0.93

(c) Lung Dose Normalized by organ-specific CTDI_{vol}

R-squared (Female) = 0.55

R-Squared (Male) = 0.86

(d) Liver Dose Normalized by organ-specific CTDI_{vol}

R-squared (Female) = 0.78

R-Squared (Male) = 0.87

FIG. 9. Gender-specific analysis performed on the lung data. Lung doses are separated into females and males and normalized by global (a), regional (b), and lung-specific CTDI_{vol} (c). All three plots demonstrate an obvious segregation between females and males in the chest models. This gender separation is not seen in the abdominal organ liver (d).

case, then methods may be available to perform this regional identification in an automated fashion; in a recent study by Sodickson *et al.*³⁸ an informatics toolkit was developed to extract anatomy-specific CTDI_{vol} values. This toolkit could be deployed to extract the desired regional CTDI_{vol} values described in this work to possibly provide a fully automated and robust estimate of patient dose that accounts for both the local effects of TCM and patient size.

This study is attempting to improve CT dose metrics such as CTDI_{vol} and SSDE, by providing better ways to estimate patient dose under TCM mode. However, it is still an estimate and therefore capable of under- or overestimating actual dose in certain situations. As the CT community is trying to come up with improved models to estimate organ dose and obtain the best size metric to correlate dose with, different groups have been exploring graphics processing unit (GPU) applications in Monte Carlo simulations to reduce the computational time of such high computationally demanding

simulations.³⁹⁻⁴¹ The results look very promising and might enable real-time Monte Carlo simulation on individual patients undergoing CT in the future; however, there are still significant remaining technical, logistical, and resource issues such as automated online segmentation of organs among others. In the interim, the methods described here hope to move our clinical practices away from CTDI_{vol} and DLP to improved dose metrics such as SSDE and beyond.

ACKNOWLEDGMENTS

This work was supported by a grant from Siemens Medical Solutions through a Master Research Agreement with UCLA Department of Radiology. The authors would also like to acknowledge previous grant support from the National Institute of Biomedical Imaging and Bioengineering NIBIB (Grant No. R01 EB004898).

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