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Relationships of Pediatric Anthropometrics for CT Protocol Selection

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Abstract

OBJECTIVE—Determining the optimal CT technique to minimize patient radiation exposure while maintaining diagnostic utility requires patient-specific protocols that are based on patient characteristics. This work develops relationships between different anthropometrics and CT image noise to determine appropriate protocol classification schemes.

MATERIALS AND METHODS—We measured the image noise in 387 CT examinations of pediatric patients (222 boys, 165 girls) of the chest, abdomen, and pelvis and generated mathematic relationships between image noise and patient lateral and anteroposterior dimensions, age, and weight.

RESULTS—At the chest level, lateral distance (*ld*) across the body is strongly correlated with weight ($ld = 0.23 \times \text{weight} + 16.77$; $R^2 = 0.93$) and is less well correlated with age ($ld = 1.10 \times \text{age} + 17.13$; $R^2 = 0.84$). Similar trends were found for anteroposterior dimensions and at the abdomen level. Across all studies, when acquisition-specific parameters are factored out of the noise, the log of image noise was highly correlated with lateral distance ($R^2 = 0.72$) and weight ($R^2 = 0.72$) and was less correlated with age ($R^2 = 0.62$). Following first-order relationships of image noise and scanner technique, plots were formed to show techniques that could achieve matched noise across the pediatric population.

CONCLUSION—Patient lateral distance and weight are essentially equally effective metrics to base maximum technique settings for pediatric patient-specific protocols. These metrics can also be used to help categorize appropriate reference levels for CT technique and size-specific dose estimates across the pediatric population.

Keywords

anthropometry CT acquisition; CT protocols; pediatric CT; pediatrics; radiation dose; size-specific dose estimation (SSDE)

There has been increasing awareness of medical radiation exposure in children and of the need to reduce exposure to as low as reasonably achievable (ALARA), particularly with

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respect to CT use in the pediatric population. The use of patient-specific protocols or of diagnostic reference levels allows imaging centers to tailor CT acquisition techniques for a specific study and subject [1, 2]. Patient-specific protocols are often based on simple measures that can be quickly determined before acquisition, such as patient weight, lateral distance, or age. The purpose of our study was to determine the relationships between age, weight, and patient dimensions and the influence of these patient characteristics on image noise in an effort to develop protocols for maximizing image quality for given patient characteristics.

One challenge to the development of optimal diagnostic reference levels in children is the wide variations and rapid growth in patient size throughout childhood. Several anthropomorphic analyses have been performed and published. Many of these studies do not report all three of the potential measures for patient categorization, and patient dimension measures are generally performed on upright, rather than supine, subjects [3]. Furthermore, increases in childhood obesity may lead to relationships that are not consistent with previously published data and size models [4, 5]. Kleinman et al. [6] presented the contemporary relationship between patient size and age at a tertiary care center in an effort to lead toward the use of more optimal x-ray exposure factors in children. Our study extends the work of Kleinman et al. by also establishing a relationship with weight and then evaluating the impact of the additional metrics of lateral and anteroposterior dimensions on image noise.

Materials and Methods

We obtained approval from the institutional review board for this retrospective study in accordance with the regulations of HIPAA.

Subject Selection

Combined CT examinations of the chest, abdomen, and pelvis performed on patients at Seattle Children's Hospital between August 18, 2008, and June 29, 2010, were reviewed. Exclusion criteria included artifacts that could preclude accurate measurements. Additionally, CT images were reviewed, and patients with diseases that could affect body region measurements were excluded. Specific exclusion criteria included metallic spinal fixation hardware and large abdominal masses. There were 387 patients with CT examinations of the chest, abdomen, and pelvis included in our study: 222 (57%) boys and 165 (43%) girls. For patients who underwent multiple examinations during the study period, only the first examination during the time period was measured.

CT Technique and Measurements

CT images were acquired on one of two scanners: LightSpeed VCT or Discovery STE (both GE Healthcare). DICOM images were transferred to a PACS equipped with software (Centricity, version 3.2.2, GE Healthcare) for JPEG lossless image data compression and storage. Images were viewed on a high-resolution monitor (6-megapixel display [Coronis, Barco]) calibrated to a gray-scale standard display function (DICOM part 14). Standard soft-tissue window and level settings were used for image display. Measurements were

performed using the ruler tool (millimeters) and oval ROI tool in PACS. Two authors made the measurements on the CT examinations: One author measured the 222 male patients and another author measured the 165 female patients.

Data Collection

We chose anatomic landmarks for measurements to ensure reproducibility. Thoracic measurements were made at the level of the right pulmonary artery (Fig. 1) and abdominal measurements were made at the level of the umbilicus (Fig. 2) on trans-axial images. Anteroposterior and lateral measurements were made along the longest central axis in each dimension. Rarely (< 5% of patients), the patient anatomy was larger than the FOV. In these cases, the anteroposterior scout view was used for the lateral measurement. The image noise at these two levels was derived from the SD of the measured signal of a 1-cm² ROI drawn in the paraspinal muscle. In a small fraction of the chest images of the smaller patients, the paraspinal muscles were not sufficiently developed to contain a 1-cm² ROI. For these images, the ROI was placed in the chest wall muscle. The voxel size, tube current–time product at the slice of interest, and tube voltage were also recorded.

Data Analysis

Prediction models were applied to determine the relationship of the lateral and anteroposterior distance measurements as a function of age and weight. Linear regression based on the model of $y = mx + b$, with the 95% CIs, was applied. For the noise analysis, the SD of CT numbers in the ROIs from the chest and abdomen levels served as the base noise level, n . This noise level was normalized between patient scans based on the first-order relationships that image variance in CT is inversely proportional to the tube current–time product (mAs) and voxel volume (mm³), so that normalized noise ($\tilde{n}$) for a single study, i , is:

$$\tilde{n}_i = \frac{1}{k_i} \sqrt{n_i^2 \frac{c_i}{c_{norm}} \frac{v_i}{v_{norm}}}$$

where c_i is the tube current–time product (mAs) for the scan; c_{norm} is the tube current–time normalization chosen as 100 mAs, representing a common setting; v_i is the voxel volume of current scan; v_{norm} is the voxel volume normalization chosen as 2.4 mm³, representing a common size (500-mm FOV, 2.5-mm-thick slice); and k_i is a factor normalizing for tube voltage, which we discuss later. Finally, the coefficient of variation (COV) of the pixel values (n'_i) was calculated as follows:

$$n'_i = \tilde{n}_i / m_i$$

where m_i represents the mean CT number in the ROI for this study.

The majority of the studies were acquired with 120 kVp; one third of the studies were acquired with 100 kVp and 18 studies were acquired with 80 kVp. To normalize the effects of the energy spectrum, we applied scaling factors based on the work by Boone et al. [7]

showing the change in noise based on tube voltage (kVp) and object size in phantom studies for a CT system manufactured by GE Healthcare. Their results show that when all other scanning parameters are fixed, the factors for noise change for a 16-cm-diameter phantom (average lateral distance for patients with 100-kVp studies = 17 cm) scanned at tube voltages of 140, 120, 100, and 80 kVp compared with 120 kVp are k_i 0.87, 1.00, 1.19, and 1.68, respectively. In other words, for fixed acquisition parameters (e.g., tube current, pitch), a 100-kVp study will have 1.19 times the noise of a 120-kVp study. We used the same factors for all patients, regardless of size, assuming to first order that these factors are, on average, close. These factors will be a function of subject size and will vary roughly by only 10% as the phantom or subject increases to 32 cm [7]. Moreover, these factors are very close to other proposed factors showing the influence of tube voltage (140, 120, 100, and 80 kVp) on changes in noise and are reported to be as follows: 0.82, 1.00, 1.27, and 2.14, respectively [8], and 0.85, 1.00, 1.28, and 1.76 [9].

Linear regression was performed between the log of the normalized COV and the lateral distance, weight, and age for both the chest and abdomen levels. This evaluation will establish which patient characteristic is a better predictor of image noise.

The goal of the last analysis was to approximate the tube current–time product that is necessary to achieve equal noise for each patient. This analysis is based on the inverse proportionality of the image variance and tube current–time product. For each study, we estimate the tube current–time product to achieve matched noise (c'_i) as follows:

$$c'_i = c_{norm} \left[\frac{n'^2_i}{n'^2_{norm}} \right]$$

where n'_{norm} is the COV normalization to 25%. In short, this equation states that if you perform an acquisition that has noise with a normalized COV of 25%, then the appropriate tube current–time product to achieve the target normalized COV of 25% is 100 mAs. If you have another acquisition with a normalized COV of 50%, then the tube current–time product will need to be increased to achieve the target COV of 25%. Specifically, the tube current–time product would need to be 400 mAs to maintain a matched noise level. The estimated c'_i is plotted versus lateral distance and versus weight.

All analyses were performed using Matlab software (version 2012b, MathWorks). Linear regression analysis was computed with 95% CIs, and exponential relationships are presented with standard errors of the estimates.

Results

Distance Versus Weight and Age

The relationship of external long-axis measurements versus age and weight are presented in Figures 3 and 4. In Figure 3, the lateral and anteroposterior distances measured at the right pulmonary artery are plotted versus age and weight. In Figure 4, the distances measured at the umbilicus are plotted. There is a strong linear relationship between these measures with

the coefficient of determination (R^2) for lateral distance to age equal to 0.84; anteroposterior distance to age, 0.75; lateral distance to weight, 0.93; and anteroposterior distance to weight, 0.90. The lower R^2 values for age compared with those for weight show that these distance measures are more a function of weight than age.

To ensure translation of the relationship between lateral distance and weight in a larger population, we performed a similar analysis on the data from a 1977 study on anthropometry of infants, children, and youths prepared for the U.S. Consumer Product Safety Commission [5]. This dataset contains lateral distance measurements at the chest level and abdomen level of 1308 children. The relationship of these lateral distance measurements with weight is presented in Figure 5.

Image Noise Versus Patient Characteristics

The logs of the normalized COV (n'_i) versus patient characteristics are presented in Figures 6 and 7. When the influence of variations in CT acquisition are removed from the noise measurements so that all studies were effectively acquired with 120 kVp and 100 mAs and were reconstructed to 2.4 mm³ pixels, these plots assess the impact of solely patient dimensions (not variations in acquisition technique) on image noise. Noise is highly correlated with lateral distance, weight, and age. At the chest level, the correlation of noise with lateral distance ($R^2 = 0.72$) is significantly higher than noise with age ($R^2 = 0.62$) ($p < 0.001$). Likewise, the correlation of noise with weight ($R^2 = 0.72$) is significantly higher than with age ($p < 0.001$). At the chest level, evidence does not support a significant difference in correlation between lateral distance and weight. At the abdomen level, the correlation is significantly higher for the lateral distance than for weight or age; noise is more a function of transverse distance than weight ($p = 0.003$) and age ($p < 0.001$).

CT Technique Versus Patient Characteristics

Plots of the estimated tube current–time product to achieve matched noise for each patient versus weight and lateral distance are presented in Figure 8. Exponential fits to these data provide a relationship that, on average, will lead to tube current–time products that can provide matched noise across different weights or different lateral distances.

Discussion

Considering the fact that the attenuation of x-rays is exponentially related to the distance they travel through the body, intuition suggests that the lateral distance of a patient would be a good predictor of CT image quality. Kleinman et al. [6] reported that age is a weak predictor of lateral distance and suggested that, because of this weak relationship, age may be a poor predictor of image quality. The prevailing practice at many imaging centers is to base pediatric protocols on patient weight, not age or lateral distance. The goal of our current work was to determine which of the following patient characteristics—lateral or anteroposterior distance, age, or weight—is a better predictor of image quality.

Distance Versus Weight and Age

Our results show the long-axis distances are highly correlated with weight ($R^2 = 0.89$) and are less correlated with age ($R^2 = 0.75$). The linear relationships for distance versus age are extremely close to those reported by Kleinman et al. [6] and fall within their CIs. For example, for lateral abdomen distance versus age, we found that $y = 0.97 \times \text{age} + 14.86$ and Kleinman et al. showed that $y = 0.93 \times \text{age} + 15.0$ [6]. The conclusion that age is a suboptimal predictor of patient size is not new and has been shown by other groups [6, 10].

For a 50-kg child, our data suggest that the lateral length at the chest was, on average, 31 cm and at the abdomen is 27 cm. For a 50-kg child in a prior anthropometry study [5], the lateral length at the chest was, on average, 25 cm and at the abdomen is 25 cm. The differences between the results of the prior study and our results may be attributed in part to the fact that the measurements for the prior study were obtained on standing subjects, whereas the measurements for our study were obtained on supine subjects. Likewise, the majority of the CT examinations for our study were performed at full inspiration, which may account for some of the relative increase in the chest dimension. Furthermore, the average girth of U.S. children has changed in the past 3 decades. Despite slightly different regression lines, both datasets show that lateral length is highly correlated with weight ($R^2 = 0.89$), suggesting that these two metrics could be used interchangeably to guide CT protocol design for examinations of pediatric patients.

Image Noise Versus Patient Characteristics

Evaluation of normalized noise levels across patients showed that noise can be predicted confidently using lateral distance, slightly less well using patient weight, and even less well using patient age (Figs. 6 and 7). Noise was more correlated with lateral distance than with weight at the abdomen level ($p = 0.003$), but evidence did not support a significant difference at the chest level. Despite a statistically significant correlation difference at the abdomen level (noise correlation with lateral distance, $R^2 = 0.86$; noise correlation with weight, $R^2 = 0.80$), there is arguably no real clinical difference in the correlations of noise with distance or weight at the chest level. Assuming noise is a surrogate for image quality, these results suggest that protocols would be best designed if they were based on external lateral distance, with patient weight being only slightly less effective. For practical purposes, we conclude that protocols can be designed on the basis of lateral distance or weight. Furthermore, age is a poor predictor of image quality and should not be used to guide CT protocol design.

Table 1 presents patient categories based on the commonly used Broselow-Luten color-coded scale [11], which is based on weight. This table includes the results from our study for mean lateral distances and mean effective diameters for each of these categories. We calculated effective diameter as follows: [effective diameter = square root of (lateral distance $\times$ anteroposterior distance)]. These three metrics—weight, lateral distance, and effective diameter—could be used interchangeably to categorize patients.

CT Technique Versus Patient Characteristics

To provide some guidance on lateral distance–based or weight-based protocols, we present the graphs in Figure 8 that show the tube current–time product settings that would achieve matched noise levels across the pediatric population. This information is not intended to provide hard rules on appropriate CT protocols. In particular, equal image noise across patient sizes will not yield equal diagnostic performance. For example, the results of CT studies of pediatric patients in the literature suggest that CT of smaller patients requires a higher signal-to-noise ratio to yield the same diagnostic performance as CT of large patients because smaller patients have smaller features to resolve [7]. The plots shown in Figure 8 are intended to provide a starting tube current–time product setting that institutions should modify (most likely increase the recommended tube current–time product for smaller patients) to match local preferences. These plots show the accepted reality that smaller patients can and should be imaged with substantially less flux than larger patients—in some cases, 40 times less flux—and that the images will still have reasonable noise levels.

Application to Size-Specific Dose Estimates

The American Association of Physicists in Medicine (AAPM) Task Group [10] proposed the use of the size-specific dose estimate (SSDE) to better reflect the absorbed dose to a patient than the conventional metric of volume CT dose index (CTDI_{vol}). The dose imparted to a patient is a function of both scanner output and patient characteristics. The CTDI_{vol} captures only information on scanner output. The SSDE, as proposed in Report 204 of the AAPM Task Group [10], converts the CTDI_{vol} to a patient-specific dose based on the patient dimensions. There are limitations to the SSDE, but in general it provides a better estimate of patient dose than CTDI_{vol} [12]. Furthermore, it has been shown that automatic exposure control intended to provide matched image quality can lead to SSDEs that are no longer a function of patient size [13]. In other words, a single value for SSDE could be used as a reference level for all patient sizes.

To place our results for patient categorization in the context of SSDE, we present SSDE conversion factors in Table 1. These factors can be used to convert a CTDI_{vol} value as measured with a 16- or 32-cm phantom into a SSDE value and were tabulated using factors for effective diameter presented in Report 204 of the AAPM Task Group [10]. Considering that weight and effective diameter are strongly correlated, as shown in Figures 3 and 4, weight could potentially be used to provide a rough conversion factor as presented in Table 1.

Clinical Impact

Our results suggest that pediatric patient–specific body CT protocols should be based on patient lateral distance or weight. Modern CT systems have automatic exposure control options that, in the ideal operating state, would automatically adjust the technique to the patient habitus based on the initial scout or localization view and during the CT acquisition. Even if a system has automatic exposure features, we assert that operators of the system should set patient-specific maximum technique settings to ensure that the CT system does not incorrectly overdose the patient. Furthermore, the use of diagnostic reference levels

should be applied in patient-specific categories, which could be based on weight or lateral distance.

Conclusion

This work shows that patient lateral distance, which can be easily measured with calipers while the patient is in the supine position before scanning, or patient weight are suitable characteristics on which to base maximum technique settings for patient-specific CT protocols. Furthermore, we provide guidance on weight-based or distance-based protocols and place these protocols in context with the SSDE.

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Fig. 1. CT scan of 16-year-old girl shows thoracic locations for measurement of noise within ROI (*circle*) and for measurements of anteroposterior (*vertical line*) and lateral (*horizontal line*) distances.

Fig. 2.
CT scan of 16-year-old girl shows abdominal locations for measurement of noise within ROI (*circle*) and for measurements of anteroposterior (*vertical line*) and lateral (*horizontal line*) distances.

Fig. 3.

Graphs show distance measurements at chest versus age and weight.

A and **B**, Lateral (**A**) and anteroposterior (**B**) distance measurements at chest level versus age.

C and **D**, Lateral (**C**) and anteroposterior (**D**) distance measurements at chest level versus weight.

Fig. 4.

Graphs show distance measurements at abdomen versus age and weight.

A and **B**, Lateral (**A**) and anteroposterior (**B**) distance measurements at abdomen level versus age.

C and **D**, Lateral (**C**) and anteroposterior (**D**) distance measurements at abdomen level versus weight.

Fig. 5.

Graphs show lateral distance measurements versus weight. Measurements were performed as part of 1977 study for U.S. Consumer Product Safety Commission [5]; this dataset contains lateral distance measurements at chest level and abdomen level of 1308 children. **A** and **B**, Lateral distance measurements at abdomen level (**A**) and at chest level (**B**) versus weight.

Fig. 6.

Graphs show log of normalized coefficient of variation (COV) at chest versus lateral distance in chest, weight, and age.

A–C, Log of normalized COV in CT numbers at chest versus lateral distance in chest (**A**), weight (**B**), and age (**C**). Normalization removes differences in CT acquisition techniques. Results show that noise is function of both weight and distance and is less function of age.

Fig. 7.

Graphs show log of normalized coefficient of variation (COV) at abdomen versus lateral distance in abdomen, weight, and age.

A–C, Log of normalized COV in CT numbers at abdomen versus lateral distance of abdomen (**A**), weight (**B**), and age (**C**). R^2 is significantly larger in **A**, which shows that noise is more function of lateral distance than weight ($p = 0.003$) and age ($p < 0.001$).

Fig. 8.

Graphs show tube current-time product to achieve matched noise levels for each weight and for each lateral distance at chest and abdomen. Exponential fit and standard error of estimate (SEE) are presented in insets.

A and B, Tube current-time product to achieve matched noise levels for each weight at chest level (**A**) and abdomen level (**B**).

C and D, Tube current-time product to achieve matched noise levels for each lateral distance at chest level (**C**) and abdomen level (**D**).

TABLE 1

Suggested Patient Categorization With Conversion Factors for Computing Size-Specific Dose Estimates (SSDEs) for Chest and Abdomen Protocols Based on Average Effective Diameter of Patients in Each Weight-Based Category

Category ^a	Patient Weight (kg)	Chest				Abdomen			
		Lateral Distance ^b at Axilla (cm)	Effective Diameter ^c at Axilla (cm)	SSDE Conversion Factor ^d for CTDI _{vol} Measured on		Lateral Distance ^b at Umbilicus (cm)	Effective Diameter ^c at Umbilicus (cm)	SSDE Conversion Factor ^d for CTDI _{vol} Measured on	
				32-cm Phantom	16-cm Phantom			32-cm Phantom	16-cm Phantom
Pink	6–7.4	15.3 ± 1.7	12.7 ± 0.9	2.33	1.15	13.9 ± 1.1	12.3 ± 0.9	2.36	1.16
Red	7.5–9.4	17.4 ± 1.3	13.6 ± 0.6	2.25	1.11	15.6 ± 1.0	13.6 ± 1.4	2.25	1.11
Purple	9.5–11.4	18.4 ± 1.5	14.0 ± 0.7	2.22	1.09	16.0 ± 1.3	13.6 ± 1.0	2.25	1.11
Yellow	11.5–14.4	19.8 ± 1.2	15.2 ± 0.8	2.12	1.04	17.0 ± 0.7	14.4 ± 1.0	2.19	1.07
White	14.5–18.4	21.4 ± 1.3	16.3 ± 0.8	2.03	1.00	18.5 ± 1.1	15.5 ± 1.2	2.10	1.03
Blue	18.5–22.4	23.2 ± 0.9	17.4 ± 0.8	1.95	0.95	19.7 ± 1.2	16.1 ± 1.3	2.04	1.01
Orange	22.5–31.4	25.0 ± 1.5	19.0 ± 1.1	1.84	0.90	21.9 ± 1.8	18.2 ± 1.8	1.89	0.92
Green	31.5–40.5	28.9 ± 2.2	21.2 ± 1.3	1.70	0.82	24.8 ± 2.3	20.0 ± 2.0	1.78	0.86
Black	40.6–55	31.4 ± 1.6	23.5 ± 1.6	1.56	0.76	27.3 ± 2.4	22.3 ± 2.4	1.63	0.79
Gray	55.1–70	34.6 ± 1.7	26.0 ± 1.3	1.43	0.69	30.5 ± 3.4	24.6 ± 2.8	1.50	0.72
Violet	70.1–100	38.5 ± 2.6	29.0 ± 2.1	1.28	0.61	33.7 ± 3.7	27.6 ± 3.2	1.35	0.64
Lavender	> 100	45.4 ± 3.5	35.0 ± 2.6	1.02	0.48	43.8 ± 4.8	36.3 ± 3.4	0.98	0.46

Note—CTDI_{vol} = volume CT dose index.

^a Patient categories are inspired by the commonly used Broselow-Luten color-coded scale [11] based on patient weight.

^b Distance measurements are from this study and are presented as mean ± SD.

^c Effective diameter measurements are from this study, are presented as mean ± SD, and were calculated as follows: [effective diameter = square root of (lateral distance × anteroposterior distance)].

^d These factors can be used to convert a CTDI_{vol} value as measured with a 16- or 32-cm phantom into an SSDE value and were tabulated using factors for effective diameter presented in [10].