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Evaluation of Size-Specific Dose Estimates for Optimizing Pediatric Chest CT Protocol

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ABSTRACT

Introduction: The importance of estimating patient-sized adjusted radiation dose for pediatric computed tomography (CT) has long been accepted. High doses of ionizing radiation to children are often common in chest CT examinations, as the volume CT dose index ($CTDI_{vol}$) is measured by a 32 cm phantom. Our study aimed to evaluate the effectiveness of size-specific dose estimate (SSDE) to compensate for the underestimated pediatric absorbed dose.

Material and Methods: $CTDI_{vol}$ and dose-length product (DLP) of 320 pediatric chest CT (<1, 1-5, 5-10, 10-15 years) were obtained from Picture-Archiving and Communication System (PACS) in a hospital affiliated with the Shiraz University of Medical Sciences. $CTDI_{vol}$ was converted to SSDE based on the patient's effective diameter. The Statistical Package for Social Science (SPSS) was used for data analysis.

Results: The variations between standard phantom (32cm) and the patients' mean effective diameter were approximately 65%, 57%, 47%, and 38%, across <1, 1-5, 5-10, 10-15 year age groups, respectively. The mean of SSDE for each age group was significantly higher than the corresponding $CTDI_{vol}$ values. Also, mean $CTDI_{vol}$ and SSDE values differed between age groups significantly ($p<0.001$). Results showed a strong correlation between age and the two-dose indicators, $CTDI_{vol}$ (*0.361*) and SSDE (*0.184*), with $p<0.05$.

Conclusion: Pediatrics receive radiation doses comparable to the dose for adult-sized patients in chest CT protocol if the dosimetry procedure is not individualized. Thus, applying a size-based conversion coefficient is paramount in estimating the absorbed dose in pediatric chest CT.

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Introduction

In recent decades, technological breakthroughs such as multiple-row detectors and helical scanning in computed tomography (CT) modality have led to increasingly widespread demand for this technique in medical care. However, despite the robustness of this imaging facility, exposure to ionizing radiation is seriously criticized [1,2]. A study done by Lee et al. [3], showed that more than 70% of physicians in the emergency departments failed to estimate the radiation dose received from abdominal CT scans correctly. This is a concern in paediatric scanning since paediatric patients are extremely sensitive to ionizing radiation (x-ray). Also, due to long life expectancy, they may experience some stochastic effects of radiation in their later life.[4] Several studies have identified risks of cancer incidence, including leukemia, thyroid, breast, brain, or skin cancer, in children due to the exposure to ionizing radiation in CT scanning procedures [5-7].

CT scanning is known as the most important source of radiation dose to the patient and is considered to contribute a large proportion of the cumulative patient dose [8-10]. Therefore, several diagnostic tools were developed during the last decades due to radiation dose reduction demands. . These include automatic tube current and tube voltage modulation, scan length optimization, and iterative reconstruction [11,12]. It is to be kept in mind that there seem to be some inconsistencies in the application of an optimized protocol for reducing unnecessary radiation to patients, especially children. Thus, accurate estimation of absorbed dose in patients has always been an area of focus, following which some dose metrics were introduced. Computed Tomography Volume Dose Index ($CTDI_{vol}$) and Dose Length Product (DLP), in spite of their limitations, also serve as useful tools to determine Diagnostic-Reference Level (DRL) and Local-Diagnostic-

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Reference Level (LDRL), which are used in CT dose optimization management. However, $CTDI_{vol}$ is not an efficient metric to estimate effective dose because it uses standard size phantom, e.g. 16cm and 32cm diameters for head and body, for dose measurement. Since the sizes of patients are not fixed (it can be smaller or larger than the standard size phantom) the CT dose indicators, which represent the patient dose, can be over (when the patient's size is larger than the standard size phantom) or under (when the patient's size is less than the standard phantom) -estimated [13-17]. Therefore, in addition to the patient's age and specific organs under the irradiation, the body size or effective diameter of the scanned area has an important role in calculating the patient dose [18-23]. Some studies demonstrated that using $CTDI_{vol}$, measured by standard phantom, yielded a 40-70 percent underestimation of the absorbed dose to the average-sized adult and paediatric torsos [24,25]. Additionally, neither volume-weighted $CTDI_{vol}$ nor DLP, which were subsequently presented, could provide accurate dose information to implement the individualized imaging protocol [13-17]. It is recommended that patients' size, irradiated organs, body composition, and scanning condition be taken into consideration to achieve an effective patient dose and to estimate potential cancer risk in them [18, 26-31]. In this regard, the use of $CTDI_{vol}$ accompanied by size-specific dose estimate (SSDE) was recently presented to meet the challenges of estimating effective dose [13, 18, 27-33].

The concept of SSDE has been neglected within CT imaging protocols for pediatric in the Shiraz University of Medical Sciences hospitals. Since the number of paediatric chests CT referred to Namazi hospital is considerably high (due to the availability of anesthesia team and related facility) it is necessary to correctly evaluate the pediatric chest CT dose based on the patient size (size-specific dose estimate or SSDE). The aim of the present study is to arrive at an improved dose estimate by using SSDE.

Materials and Methods

Clinical data

This retrospective study was conducted by extracting the dose indicators including, volume $CTDI_{vol}$ and DLP, available on the page of the dose report, for 320 patients aged ≤15 years old (y/o) who were admitted to the Namazi hospital for chest CT, during 2017-2018. The pediatric patients were categorized into 4 age groups <1, 1-5, 5-10, 10-15-year-old. This categorization was done based on the recommendation given by Vassileva et al [34].

Chest CT images were acquired in axial and helical modes on GE (LightSpeed16) and Philips (Brilliance16) Multi-Detector CT (MDCT) scanners, both from the United States. Filter-Back Projection (FBP) was used to reconstruct CT images by using a 512×512 matrix in both the CT systems. This is the reconstruction protocol that is generally accessible in CT scanners available in Iran. The chest CT protocols dominantly used 120 kVp (except for a few cases which were scanned by 80 or 100 kVp), mAs modulation mode, 1.75 pitch factor, and 2 to 5 mm reconstructed slice thickness. The chest CT images, for which the page of the dose report was not saved, were excluded. Size-Specific dose estimate (SSDE) was calculated by the product of the $CTDI_{vol}$ and the conversion factor, found from the American Association of Physicists in Medicine (AAPM) Report number 204 [35], for 32cm CTDI phantom. An axial slice of chest CT image just before the bifurcation of the aorta was selected as a reference slice (the largest slice in the chest region) [22]. A digital ruler was used to measure the lateral (LAT from side to side of the chest) and Antro-Posterior (AP) dimensions of the pediatric cheat CT, as can be seen in Fig (1). It has to be noted that to be more definite about the accuracy of the dimension measurement, we have repeated the same procedure for 3 more slices below and above the reference slice. The differences between consecutive measurements were negligible. As is known, phantoms (used to measure $CTDI_{vol}$) are circular cylinders while the human body can be thought of as being rough of an elliptical shape. For an ellipse with a semi-major axis "a" and semiminor axis "b" the area of cross-section is $A = \pi \times (a \times b)$, which is equal to that of a circle with a radius $r = \sqrt{a \times b}$. In the present case, we use a = (lateral/2) and b = (AP/2) dimensions, which makes $effective\ diameter = 2r = \sqrt{LAT \times AP}$. Next, using the above value of "r" we find the necessary conversion factor from the AAPM document [35]. The SSDE is then calculated as,

$$SSDE = CTDI_{vol} \times Conversion\ Factor \quad (1)$$

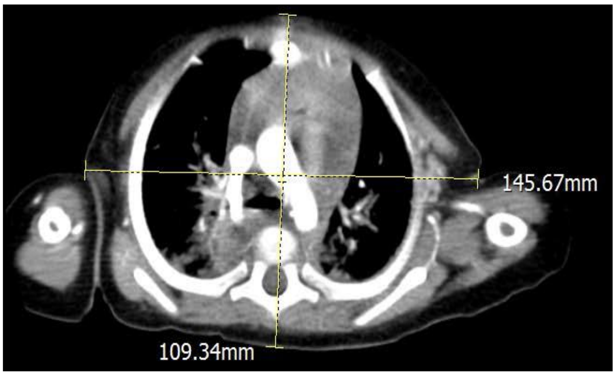

Figure 1. Axial slice of chest CT image, just before bifurcation of aorta, both horizontal and vertical yellow lines were used to measure the Lateral (LAT) and Antero-Posterior (AP) dimensions of the pediatric patient.

Statistical analysis

SPSS version 19.0 was used to statistically evaluate the obtained data. To begin with, the Kolmogorov-Smirnov test was used to assess the normality of the data; and Levene's test was used for homogeneity of variances. The variables were expressed as descriptive statistics (mean and standard deviation). The differences between the means of $CTDI_{vol}$ and SSDE values for each age group were tested by the Wilcoxon test. Furthermore, the Kruskal-Wallis test determined the significance of the mean difference in $CTDI_{vol}$ and SSDE values between 4 age groups by *p*-values lower than 0.05, as a significance level. We took advantage of Spearman correlation analysis to determine the strength of the association between age and CTDI and SSDE quantities.

Box and Whisker plots were used to show the distribution of $CTDI_{vol}$ and SSDE values in 4 age categories. These enabled the comparison of the $CTDI_{vol}$ and SSDE values, through which we were provided with evidence on the performance of SSDE in measuring the chest CT absorbed dose.

Results

Of all the pediatric patients, involving 138 girls and 182 boys, the mean age was 6.46 ±4.72 (range, 1 month to 15 years) years. While the measured effective diameter of the chest in the pediatric demonstrated a median of 14.83 cm, the mean effective diameter for four different age groups is as follow (see Table 1): up to 1 year was 11.02 cm (range, 6.44-13.92; SD, 1.73); between 1 to 5 years was 13.53 cm (range, 9.91-19.35; SD, 1.57); between 5 to 10 years was 16.66 cm (range, 12.28-27.78; SD, 2.47); between 10 to 15 years was 19.55 cm (range, 12.67-26.02; SD, 2.71). Therefore, concerning 32 cm PMMA (polymethylmethacrylate) phantom, which is used to measure $CTDI_{vol}$, there were variations of approximately 65% (11.02/32), 57% (13.53/32), 47% (16.66/32), and 38% (19.55/32) in terms of the chest pediatric from the age of <1-, 1-5-, 5-10-, and 10–15-years-old, respectively.

We aimed to check how the distribution of $CTDI_{vol}$, DLP, and SSDE differed between different groups and also from the overall distribution that covers all the groups. We first discuss the overall distribution that involves all these 320 patients from all the groups. For this, the mean of the distribution of $CTDI_{vol}$ and DLP of the chest CT examinations for all the age groups were estimated as 4.37±2.90 mGy and 102.33±75.77 mGy.cm respectively. The estimated mean ± standard deviation of SSDE (which was determined by CTDI-to-SSDE conversion factors for 32 cm phantom) for all age groups was 8.91±5.99 mGy.

We next focus on the same parameters for different groups. The CT dose indicators are presented in Table 2. It can be seen that the means for the SSDE were greater than those for $CTDI_{vol}$ across each age group. The ratio of SSDE to $CTDI_{vol}$ is about 2.47, 2.24, 2, and 1.76, for the patients aged <1, 1-5, 5-10, and 10-15 years old, respectively. The highest $CTDI_{vol}$ to SSDE ratio belongs to the youngest group or up 1-year-old pediatric patient. Wilcoxon test showed the mean $CTDI_{vol}$ and SSDE values within all age groups differed significantly ($p<0.05$) as well. On the other hand, the $CTDI_{vol}$ values increased as age groups increased. While the highest values of mean $CTDI_{vol}$ and SSDE can be the found for 10- to 15 years-old age group, the comparison of both quantities between the age groups showed significant differences (Table 2, $p<0.05$).

Figures (2) and (3) illustrate the median and interquartile range of $CTDI_{vol}$ and SSDE parameters of the chest CT examination for each of the age groups (<1, 1-5, ,5-10 and 10-15 years old). According to Figs (2) and (3), in terms of 25 percent of children under 1 year of age, the SSDE index could determine the absorbed dose values approximately three times the values obtained for $CTDI_{vol}$, while for the other age groups, this ratio is almost double. The third quartile of SSDE is about two times higher than that of $CTDI_{vol}$ in each age group. The ratio of 75 percentiles of SSDE to 75 percentiles of $CTDI_{vol}$ are 2.4, 2.4, 1.75 and 1.85 for less than 1, 1-5, 5-10, and 10-15 years old, respectively. Also, the trend of the median values is found to be similar.

In addition, age influenced the $CTDI_{vol}$ and SSDE values with significantly positive correlation strengths of 0.361 and 0.184, respectively ($p<0.05$). Figure 3 depicts the correlation between $CTDI_{vol}$ and SSDE values for different age groups. The SSDE values for all age groups demonstrated a strong positive linear correlation ($r^2>0.83$) with the corresponding $CTDI_{vol}$ values obtained from the CT system.

Table 1. Mean and standard deviation of effective diameter of pediatric chest in four age groups (<1, 1-5, 5-10 and 10-15 year).

Age group (year)	Mean age in each group ± SD* (year)	Number of patients in each group	Number of female patients	Number of male patients	Effective diameter (Mean ± SD) in cm
<1	0.287 ± 0.09	66	28	38	11.02 ± 1.73
1-5	3.63 ± 0.21	88	39	49	13.5 ± 1.57
5-10	8.62 ± 0.38	79	31	48	16.66 ± 2.47
10-15	13.39 ± 0.35	87	40	47	19.55 ± 2.71

SD*, Standard deviation

Table 2. Mean and standard deviation of $CTDI_{vol}$, SSDE and the differences between SSDE and $CTDI_{vol}$ (Δ) for pediatric chest CT examination in four age groups (<1, 1-5, 5-10 and 10-15 year)

Age group (year)	$CTDI_{vol}$ (mGy) mean±SD*	SSDE (mGy) mean±SD	Δ**	SSDE/$CTDI_{vol}$	P-value
<1	3.62±3.43	8.96±9.04	5.33±5.55	2.47±2.64	<0.001
1-5	3.71±2.21	8.31±4.74	4.63±2.57	2.24±2.13	<0.001
5-10	3.83±2.03	7.64±3.99	3.84±2.06	1.99±1.96	<0.001
10-15	6.10±3.08	10.65±5.42	4.83±2.49	1.75±1.76	<0.001
p-value	<0.001	<0.001	<0.001	<0.001	<0.001

$CTDI_{vol}$, volumetric computed tomography dose index; SSDE, Size-Specific Dose Estimate; significant level: p<0.05; SD*, Standard deviation; Δ**, is the differences between SSDE and $CTDI_{vol}$ (SSDE-$CTDI_{vol}$)

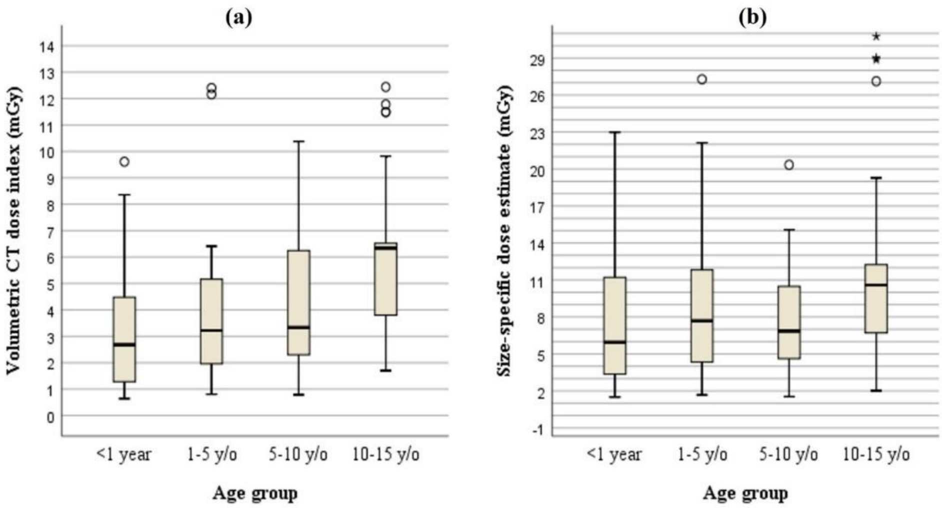

Figure 2. Distribution of dose indicators (a) volumetric CT dose index or CTDIvol, (b) size-specific dose estimate or SSDE in 4 age groups, <1 year, 1-5, 5-10, and 10-15 years old.

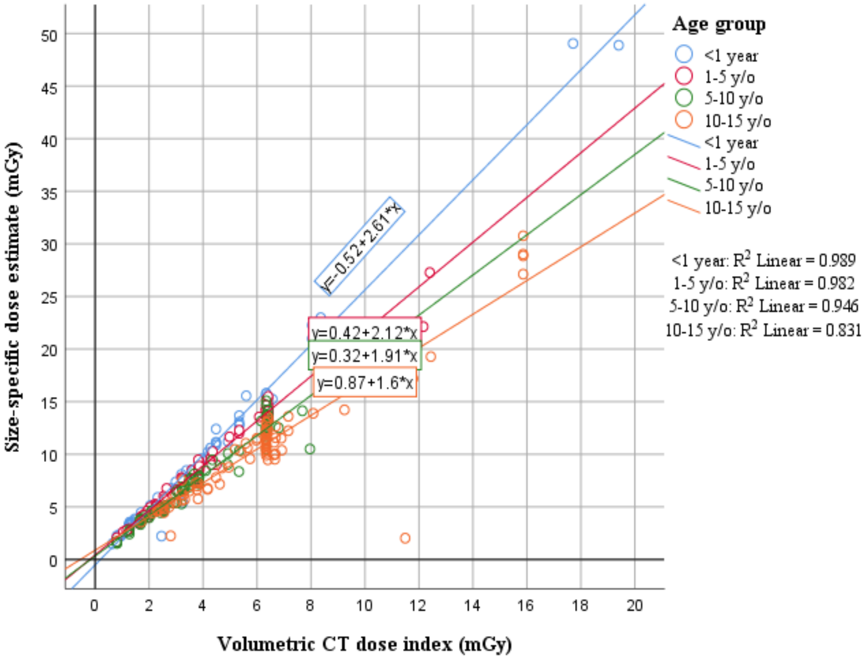

Figure 3. The Correlations between $CTDI_{vol}$ (volumetric CT dose index) and SSDE (size-specific dose estimate) for all age groups are satisfactory.

Discussion

We found in practice in all pediatric chest CT protocols (up to 1, between 1 to 5, 5 to 10, and 10 to 15 years old), that a 32cm PMMA phantom was used for dose estimation. While the mean effective diameter of pediatric patients in the present study was 15cm, which is about 2 times less than the body phantom size. Our data revealed that the mean $CTDI_{vol}$ values, obtained from the page of the dose report, were considerably lower than the mean of SSDE for each of the age categories. The mean ratio of SSDE to CTDIvol is found to be about 2.11 for all age groups (<1, 1-5, 5-10, and 10-15 years old) as is stated in Table 2, while the highest ratio is for patients who are less than 1-year-old patient (Table 1). As a result, by using the results from the 32 cm diameter $CTDI_{vol}$ phantom for pediatric chest CT imaging, children are exposed to unreasonably high dose of radiation. This finding of the present study is in broad agreement with the results published in the literature [13, 27,28,32,33]. For example, recent study with pediatric patient, zero to 16 years old, also confirms that $SSDE/CTDI_{vol}$ = 2.0, as stated "it was clearly observed that SSDE (mean) values are approximately twice the $CTDI_{vol}$ at every scan range and patient group" [36]. This is exactly what we have stated in the above lines.

Again the results of a study conducted by Chaparian et al. showed that the carcinogenesis effects of the CT angio should not be neglected. They have stated that the stochastic effects such as malignancy induction is age and sex dependent [29-31]. In this respect the aim of our study is very important and topical for the medical community.

It is worth noting that dose metric distributions at a local level or within an institute should be calculated as mean, in spite of setting those on 75th percentile at national level [37]. Nontheless, to rigorously analyze patient-sized adjusted radiation dose levels, 25th, median, and 75th percentile $CTDI_{vol}$ in present study were evaluated and found to be lower (approximately half) than those for SSDE. This showed the necessity of taking into account the patient size or its effective diameter in the scanned area to estimate a more realistic radiation dose to the pediatric and to predict the absorbed dose. This result supports the results of references [38-41] which gave a practical patient-sized formula for the regulation of dose from CT. There, however, seems a requirment to consider scan length and DLP index in conjuction with $CTDI_{vol}$ and SSDE in order to scrutinize patient dose estimate accurately.

The results of the present study showed that there is a linear correlation between $CTDI_{vol}$ and SSDE, regardless of age. However, age influenced the $CTDI_{vol}$ and also SSDE noticeably.

This study demonstrated that the effective diameter of the pediatric patient is much less than the 32 cm diameter standard phantom which is used to determine $CTDI_{vol}$. As a result, the SSDE was higher than the $CTDI_{vol}$ reported in the page of dose report which is accessible at the end of the CT image series. This is also supported by the results of Özsoykal et al in Ref [36].

This study thus leads us to address the question of dose optimaziation for pediatric chest CT protocol in order to reduce patient dose and as a result to minimize the probability of incidence of x-ray stochastic effects.

Lastely, the AAPM has in 2014 [42] released a protocol for more accurate calculation of the SSDE. This protocol was followed in Özsoykal et al study [36], but gave essentialy similar results, as we have stated in an earlier paragraph. In making estimates we have followed AAPM 204 [35]. It is to be noted that the AAPM 220 also advises that AAPM 204 can be follwed untill updated machines incorporate the advisery of AAPM 220. In particular, AAPM 220 states "even though use of D_w is recommended, when only geometric data are available to the user, it is still reasonable to calculate SSDE based on any of the geometric input parameters shown in Report 204: AP, LAT or AP+LAT, or effective diameter" [42]. It is for this reason that AAPM 204 continues to be followed by the medical physics community.

Limitation of the study: Although "SSDE" is better than "$CTDI_{vol}$", for measuring organ dose and carcinogenic risk, however, they require special computational programs [29-31].

Conclusion

The age parameter should be taken as an important factor in determining the effective diameter, by which we would be able to determine size-specific conversion coefficients. Therefore, in order to estimate the more reliable pediatric patients' dose in chest CT protocol, SSDE conversion factors have to be used to correct the underestimation of pediatric dose resulted from $CTDI_{vol}$ measurement. Optimization of pediatric chest CT protocol by selecting proper phantom size is thus neccesary.

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