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ORIGINAL ARTICLE

Size-specific dose estimates in chest, abdomen, and pelvis CT examinations of pediatric patients

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PURPOSE
Size-specific dose estimates (SSDEs) are the latest focus of interest among medical physicists studying radiation dose to the patient in computed tomography (CT). This study aims to make conversions from $CTDI_{vol}$ to SSDE and investigate the relationship between mean SSDE ($\overline{SSDE}$) and central SSDE ($SSDE_{center}$) values for pediatric patients of different age groups undergoing chest, abdomen, and pelvis scans.

METHODS
In this retrospective study, we examined 105 consecutive pediatric CT exams of chest, abdomen, and pelvis (CAP) classified in 3 separate groups according to age: 0–5 years, 6–10 years, and 11–16 years. A MATLAB program was developed to determine $\overline{SSDE}$ values for each patient along 6 subregions: chest, abdomen, pelvis, chest and abdomen, abdomen and pelvis, and CAP. SSDE values derived over the slice at the center of each scan range ($SSDE_{center}$) were also recorded. $\overline{SSDE}$ and corresponding $SSDE_{center}$ results were compared for each age group.

RESULTS
Root mean square differences (RMSD) between $\overline{SSDE}$ and $SSDE_{center}$ values ranged between 0.13 mGy and 2.1 mGy through all groups and subregions, corresponding to 1.2% and 11%, respectively.

CONCLUSION
In pediatric CT exams involving CAP region, $CTDI_{vol}$ and the water equivalent diameter at the middle of the scan range can be used to provide a reasonable estimate of mean SSDE with an RMSD of 11% at most.

The concept of computed tomography dose index (CTDI) was introduced by Shope et al. (1) in 1981 as an indicator of radiation dose output from a series of adjacent computed tomography (CT) scans. CTDI methodology, which has been proposed against multiple scan average dose methodology, helped to avoid considerable handicaps such as time consuming multiple scans and high tube loadings. Today, quantities like dose length product (DLP) and effective dose which represent radiation dose and risk originating from a CT exam are estimated based on CTDI. However, considerable advances observed in CT technology and scanning conditions in the last few decades brought CTDI concept to a quite controversial position by means of its technical inaccuracy and inconvenience to act as an indicator of patient dose (2).

Radiation output of a CT scanner is represented by CTDI volume ($CTDI_{vol}$) parameter in the dose report, which originates from the average absorbed dose measured along 100 mm at 5 different positions of a cylindrical polymethylmethacrylate phantom. The phantom may be either 16 cm or 32 cm in diameter according to the size of the scanned patient. $CTDI_{vol}$ information includes preset exposure parameters such as tube voltage (kVp), effective tube current time product (mAs), and pitch. However, it does not take patient-specific factors such as size or radiation attenuation properties into account. Therefore, $CTDI_{vol}$ cannot directly correspond to patient dose and needs to be converted into a quantity that considers patient's anatomic information as well (2, 3).

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In recent years, some important studies have been conducted for this common purpose (4–11). American Association of Physicists in Medicine (AAPM) has published two reports recommending the use of conversion factors corresponding to different patient size values for the determination of size-specific dose estimates (SSDE) (7, 8). In the first report, AAPM 204, the conversion factors have been tabulated based on the geometric dimensions of the cross-sectional image. However, in the studies carried out afterwards, it has been shown that the water equivalent diameter (D_w) acts as the most appropriate size indicator since it discriminates between different body regions with similar geometric dimensions but different attenuation properties (thorax, abdomen, pelvis) (9, 10). Thereafter, as mentioned in the AAPM Report 220, using D_w based conversion factors ($f\,D_w$) and $CTDI_{vol}$ values for each longitudinal position (i.e., slice) (z) of the image, one can determine the SSDE, as in Eq. 1.

$$SSDE(z) = f\,D_w(z) \times CTDI_{vol}(z) \quad (1)$$

SSDE, as defined in Eq. 1, is a function of "z" which represents the longitudinal axis position of the patient. Each axial slice leads to a different SSDE result due to its unique attenuation property. This generates a series of different SSDE values along the body of the patient. However, in most cases it is preferable to introduce a single dose value that can represent the entire scan. Mean SSDE value is calculated with the primary concern to achieve this goal. However, this requires slice-specific $f\,D_w$ values and scan-specific $CTDI_{vol}$ to be known in order to determine a mean SSDE ($\overline{SSDE}$) for the entire scan range. This method includes a series of calculations that, due to the complex nature of the method, cannot be completed manually. In the AAPM Report 220, a secondary method has been recommended owing to the need for a more practical $\overline{SSDE}$ calculation (8). This method makes use of the ($f\,D_w$) obtained only from the central slice of the scan range and the scan specific $CTDI_{vol}$ value to make an estimate of $\overline{SSDE}$. This time the calculated parameter is named as $SSDE_{center}$. In the study of Leng et al. (11) this method has generated acceptable results for adult patients undergoing chest, abdomen, and pelvis (CAP) CT exam.

Longitudinal variations in D_w are smaller in pediatric patients, who are smaller in size compared to adults. This may lead to the assumption of observing smaller variations in ($f\,D_w$) and therefore in the SSDE values determined along the longitudinal axis. However, since the ($f\,D_w$) is an exponential function of D_w, changes in the smaller values of D_w will result in relatively larger differences in SSDE values. For example, for the conversion of $CTDI_{vol}$ recorded on a body phantom, the difference between the ($f\,D_w$) values corresponding to 24 cm and 30 cm D_w is 0.3. But the same difference between 10 cm and 16 cm is 0.5. This indicates a ratio of about 60% between the two D_w ranges for the same magnitude of 6 cm. Therefore, for pediatric patients, the conversion factor plays a more important role on the slice by slice differences in SSDE. Thus, it possibly may yield a dramatic difference between $\overline{SSDE}$ and $SSDE_{center}$ values. For this reason, while stating the validity of $SSDE_{center}$ method for adults, Leng et al. (11) excluded pediatric patients from the scope and emphasized the need for a further study on this basis.

This study aims to investigate the convenience of $SSDE_{center}$ calculation for pediatric patients undergoing CAP scans. Since patients from different ages have different body compositions, patient cohort was divided into 3 groups according to age and the results were considered separately according to each group. In addition, overall results from all of the patients were recorded regardless of age. A MATLAB (The MathWorks, Inc.) algorithm were constructed for the necessary computations in order to achieve this goal.

Main points

- $CTDI_{vol}$ information given in the dose report following a CT scan does not account for the patient size; however, it can be used to give more patient-specific results.
- Size-specific dose estimate (SSDE) is the final dose quantity resulting from the multiplication of $CTDI_{vol}$ and a conversion factor based on patient size.
- Determination of SSDE for a single scan requires a complex series of calculations that include image processing, making manual application impossible. Hence, a practical method of $SSDE_{center}$ can be followed to predict the approximate SSDE for the pediatric patients.
- When a region of interest surrounding the patient cross-section at the center of the longitudinal scan range is drawn following the scan, mean HU, area of the region of interest and the scan specific $CTDI_{vol}$ information could help the clinical user determine $SSDE_{center}$ as a successful proxy for $\overline{SSDE}$.

Methods

Quality control of the CT scanner

A dosimetric quality control was carried out on CT scanner prior to the study in order to make sure that $CTDI_{vol}$ values obtained from the CT console are accurate. Standard measurement protocol recommended by the International Atomic Energy Agency (IAEA) was followed in the test (12). Scans were carried out on a CTDI body phantom where an ionization chamber was used for dose measurements.

MATLAB software and image processing

A program was written using MATLAB in order to utilize the images in a series of processes and eventually to calculate the SSDE values for each slice. Primarily, the reconstructed CT images were taken from the picture archiving and communication system (Fig. 1a). The program was firstly designed upon the exclusion of irrelevant objects such as the CT table and the patient cover sheet or clothes from the original image. For this purpose, a threshold value was determined to be applied among the pixels within a Hounsfield Unit (HU) range of -1000 and +3000. The value of threshold was determined via trial and error until a regular segmentation of the body contour was achieved. As a result, a binary image was obtained with only pixel values of "0" and "1". This led to the contouring of region of interest represented by the area of cross-sectional patient anatomy (A_{ROI}) (Fig. 1b, 1c). Last step was taken to omit the pixels remaining outside A_{ROI} (Fig. 1d).

Patient profile, scan protocol and scan ranges

This retrospective study was conducted in accordance with ethical standards under the responsibility of institutional review board that has approved the study (Decision no: 2015/21-20).

A total of 105 consecutive pediatric CAP exams were included. Scans were collected from 64 slice Philips Brilliance CT scanner in the Radiology Department. It was important for the patient to be positioned at the center of the gantry prior to the scan. Otherwise, the actual size of the patient could be magnified or shrinked in the image and this

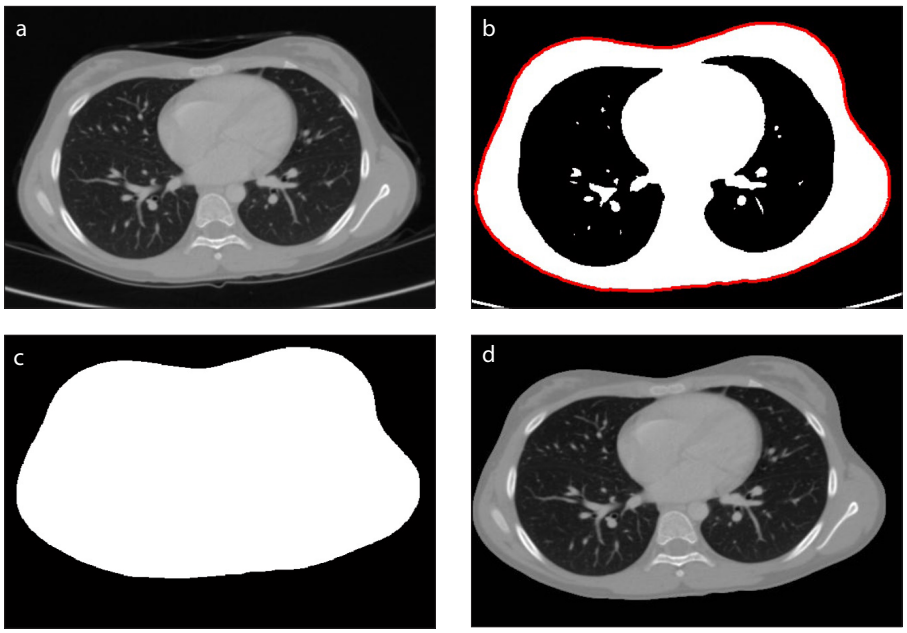

Figure 1. a–d. Reconstructed image **(a)** originally includes cross-sectional image of the patient, table and the other objects such as sheet or clothes on the patient. Binary image **(b)** shows a contour of the patient cross-section. Image **(c)** shows the discrimination of the pixels following the contouring process in order to identify A_{ROI}. Final image **(d)** has the patient table and irrelevant objects eliminated.

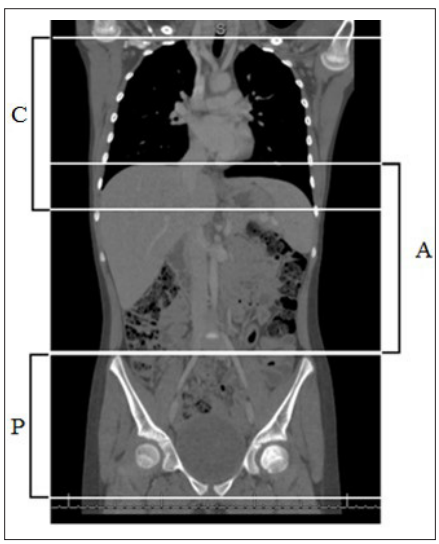

Figure 2. Anatomic markers indicate the beginning and end of chest (C), abdomen (A), and pelvis (P).

could have generated misleading results. Image selection has been performed based on this regard. The study cohort was divided into 3 groups according to patient age. First group of patients referred to a range of 0–5 years (n=33), while the second and the third groups consisted of 6–10 years (n=40) and 11–16 years (n=32), as shown in Table 1. On the other hand, overall data from all patients were compiled regardless of age in order to demonstrate the significance of subgroup results.

All scans followed routine scan protocol where the entire CAP region was included. Tube voltage and tube current were selected manually by the user prior to the scan and they were kept constant during the scan, i.e., no tube current modulation technique was used. Tube voltage was selected in the range of 80–120 kVp and tube current in the range of 50–180 mA, adjusted according to the patient size. Images were obtained with a collimation of 64×0.625 mm and reconstructed into slices 2 mm thick. Other scan parameters such as rotation time, pitch and increment were set to 0.5 s, 0.891, and 0.5 mm, respectively.

Six subregions were determined for each exam: chest, abdomen, pelvis, chest and abdomen, abdomen and pelvis, and CAP. Anatomic markers used to separate each region were determined as top and bottom of the lungs, top of the liver and pelvic crest, top of the pelvic crest and pubic symphysis, respectively, for chest, abdomen, and pelvis (Fig. 2).

Calculation of D_w and $f D_w$ parameters for each image slice

Following image processing, every slice of image underwent a computational procedure to determine the water equivalent area (A_w) with respect to the radiation attenuation properties, as shown in Eq. 2a (8).

$$A_w = A_{ROI}\left[\frac{1}{1000}\overline{CT(x,y)}_{ROI} + 1\right] \quad (2a)$$

Here, $\overline{CT(x,y)}_{ROI}$ represents the mean CT or HU number of the pixels making up the patient cross-sectional area, A_{ROI}. With the assumption of a circular A_{ROI}, D_w was determined by Eq. 2b.

$$D_w = 2\sqrt{\frac{A_w}{\pi}} \quad (2b)$$

Subsequent to the determination of D_w for each slice, ($f D_w$) calculation was carried out as in Eq. 3 (7).

$$f D_w(z) = 3.704369 \times e^{-0.03671937 \times D_w(z)} \quad (3)$$

Arithmetic mean of SSDE over the scan range: $\overline{SSDE}$

All SSDE values along the CAP scan range were calculated using Eq. 1 and recorded for each exam. In the next step, with the use of Eq. 4 shown below, the arithmetic means were calculated over each of 6 scan ranges to determine the $\overline{SSDE}$.

$$\overline{SSDE} = \sum_{z=1}^{N}\frac{SSDE(z)}{N} = \frac{1}{N}\sum_{z=1}^{N} CTDI_{vol}(z) \times f_{D_w}(z) \quad (4)$$

Here, N stands for the total number of slices each of which is represented by z. $CTDI_{vol}(z)$ is a slice specific information and given in the DICOM header for the slice.

Mean SSDE over the central slice of each scan range: $SSDE_{center}$

Making SSDE conversions in every slice of the image and then taking the arithmetic mean requires a complex series of calculations, as mentioned. Instead, it is much more practical to determine and make use of a single reference slice and generate a reasonable $\overline{SSDE}$. Therefore, Eq. 5 shows calculation of a practical and reasonable estimate of $\overline{SSDE}$.

$$SSDE_{center} = \overline{CTDI}_{vol} \times f D_w(Z_{center}) \quad (5)$$

Here, "Z_{center}" represents the central slice and $\overline{CTDI}_{vol}$ is the mean $CTDI_{vol}$ value displayed on the console screen.

Statistical analysis

Mean D_w ($\overline{D}_w$) and $D_{w,max} - D_{w,min}$ values were recorded for each patient. Then, the mean values of these parameters were taken for each patient group to make a comparison across the groups based on varia-

tions in size that will influence the SSDEs. $CTDI_{vol}$, $\overline{SSDE}$, and $SSDE_{center}$ values were also determined and recorded for all groups and subregions. Furthermore, root mean square differences (RMSD) analysis and linear regression analysis were performed on $\overline{SSDE}$ and $SSDE_{center}$ values, as shown in the Eq. 6 and Eq. 7, respectively.

$$RMS = \sqrt{\frac{\sum_{i=1}^{n}\left(\overline{SSDE}(i) - SSDE_{center}(i)\right)^2}{n}} \quad (6)$$

$$SSDE_{center} = a \times \overline{SSDE} + b \quad (7)$$

Table 1. Patient age groups

Patient group	Age range (years)	Mean age (years)
1 (n=33)	0–5	3.2
2 (n=40)	6–10	7.8
3 (n=32)	11–16	13.0
Total (n=105)	0–16	7.9

Results

The results of the dosimetric quality control test that was performed on the scanner were observed to be within the tolerance level of 20% stated by the IAEA.

For all groups, Table 2 shows the mean $\overline{D}_w$ results together with the mean percentage variation in $\overline{D}_w$, observed along each subregion. These results are important to show that the percentage variations in D_w along each subregion are more or less the same for each patient group.

Table 3 demonstrates the mean values of $CTDI_{vol}$ and $\overline{SSDE}$ for all patient groups.

Table 2. Mean values of $\overline{D}_w$ and the mean percentage variation $\left[\left(\frac{D_{w,max} - D_{w,min}}{\overline{D}_w}\right)\right]$ along each subregion

Age		C	A	P	CA	AP	CAP
0–5	$\overline{D}_w$ (cm)	15.1	15.7	14.6	15.3	15.2	15.1
	Mean variation (%)	23	20	12	25	22	26
6–10	$\overline{D}_w$ (cm)	18.0	18.8	18.7	18.3	18.8	18.4
	Mean variation (%)	22	19	11	22	20	23
11–16	$\overline{D}_w$ (cm)	21.3	21.9	23.3	21.5	22.6	22.1
	Mean variation (%)	19	18	13	19	21	23
0–16	$\overline{D}_w$ (cm)	18.1	18.8	18.8	18.3	18.8	18.5
	Mean variation (%)	21	19	12	22	21	24

$\overline{D}_w$, mean equivalent water diameter; $D_{w,max}$, maximum equivalent water diameter; $D_{w,min}$, minimum equivalent water diameter; C, chest; A, abdomen; P, pelvis; CA, chest and abdomen; AP, abdomen and pelvis; CAP, chest, abdomen, and pelvis.

Table 3. Mean values of $CTDI_{vol}$ in mGy

Age		C	A	P	CA	AP	CAP
0–5	$CTDI_{vol}$	4.93	4.93	4.93	4.93	4.93	4.93
	$\overline{SSDE}$	10.5	10.3	10.7	10.4	10.5	10.5
6–10	$CTDI_{vol}$	7.83	7.83	7.83	7.83	7.83	7.83
	$\overline{SSDE}$	14.8	14.4	14.3	14.7	14.4	14.6
11–16	$CTDI_{vol}$	11.7	11.7	11.7	11.7	11.7	11.7
	$\overline{SSDE}$	19.7	19.5	18.3	19.7	18.9	19.2
0–16	$CTDI_{vol}$	8.07	8.07	8.07	8.07	8.07	8.07
	$\overline{SSDE}$	14.9	14.6	14.4	14.8	14.5	14.6

$CTDI_{vol}$, computed tomography dose index – volume; $\overline{SSDE}$, mean size-specific dose estimate; mGy, milli Gray; C, chest; A, abdomen; P, pelvis; CA, chest and abdomen; AP, abdomen and pelvis; CAP, chest, abdomen, and pelvis.

As expected, $CTDI_{vol}$ was observed to be constant along the entire scan range due to constant tube current. However, this is not the case for $\overline{SSDE}$, which depends on the size of the patient as well as the scan parameters.

RMSD analysis showed that the difference between $\overline{SSDE}$ and $SSDE_{center}$ was in the range of 1.2% and 11% (Table 4) while the results from regression analysis performed over each patient group at every scan range showed strong correlations between the two parameters (R^2>0.973 and $P < 0.001$) (Table 5).

Discussion

Since CTDI does not correspond to patient dose in CT examinations, SSDE has been the main focus of recent studies (4–11). In this study, a MATLAB program was written to make SSDEs using $CTDI_{vol}$ and water equivalent diameter based on patient size. In addition, a manually applicable method was used to derive approximate SSDEs for pediatric examinations of the torso. This method was suggested for adults by Leng et al. (11) and introduced the use of $SSDE_{center}$ to the literature. However, it has not been validated on pediatric patients. The purpose of this study was to investigate the validation of $SSDE_{center}$ method on pediatric patients across different age groups.

Table 2 roughly indicates that the relative changes in D_w along the longitudinal axis of the patients are similar across the same scan ranges. However, there are some noticeable differences among the groups which may influence the difference between the results coming from $SSDE_{center}$ method for 6 scan ranges. The age groups displayed slightly different D_w profiles when chest, abdomen and pelvis are treated consecutively. For the first group, chest and pelvis are observed to have similar $\overline{D}_w$ values, while abdomen has the highest $\overline{D}_w$. For the second group, chest has the lowest $\overline{D}_w$, while abdomen and pelvis are observed close to each other. However, in contrast to the first two groups, the results of the third group indicate that the $\overline{D}_w$ of pelvis exceeds the $\overline{D}_w$ of abdomen and chest. This may be due to the enlarged, denser bone tissue in pelvis at 11–16 years. Parallel to this, one may also notice that the relative difference in D_w is slightly higher in the pelvis region of the third group, compared with the first two groups.

There is a noticeable difference between the anatomic structure of chest, abdomen

Table 4. Root mean square differences between $\overline{SSDE}$ and $SSDE_{center}$

Age		C	A	P	CA	AP	CAP
0–5	RMSD (mGy)	0.28	0.38	0.13	0.55	0.47	0.59
	RMSD (%)	2.6	3.7	1.2	5.3	4.5	5.6
6–10	RMSD (mGy)	0.37	0.53	0.24	0.72	0.85	0.58
	RMSD (%)	2.6	3.8	1.7	5.0	6.0	4.1
11–16	RMSD (mGy)	0.50	0.67	0.40	1.4	2.1	0.81
	RMSD (%)	2.5	3.4	2.2	7.1	11.0	4.2
0–16	RMSD (mGy)	0.39	0.54	0.28	0.95	0.98	0.67
	RMSD (%)	2.6	3.7	1.9	6.4	6.8	4.6

RMSD, root mean square difference; $\overline{SSDE}$, mean size-specific dose estimate; $SSDE_{center}$, size-specific dose estimate in the central slice of scan range; C, chest; A, abdomen; P, pelvis; CA, chest and abdomen; AP, abdomen and pelvis; CAP, chest, abdomen and pelvis.

Table 5. Linear regression analysis between $SSDE_{center}$ and $\overline{SSDE}$ and the resulting coefficients of linear regression models ($SSDE_{center} = a \times \overline{SSDE} + b$)

Age		C	A	P	CA	AP	CAP
0–5	a	1.01	1.01	1.00	0.956	1.01	0.951
	b	0.041	0.032	-0.002	0.075	0.231	0.108
	R^2	0.998	0.995	0.999	0.996	0.996	0.995
6–10	a	1.01	1.00	0.996	0.984	1.04	0.963
	b	0.087	-0.00	-0.048	-0.073	0.174	0.208
	R^2	0.998	0.993	0.999	0.990	0.995	0.995
11–16	a	1.02	0.964	0.971	1.07	1.07	0.957
	b	0.012	0.856	0.481	-0.997	-0.220	0.860
	R^2	0.998	0.992	0.997	0.973	0.990	0.986
0–16	a	1.01	0.993	0.988	1.03	1.06	0.981
	b	0.006	0.195	0.115	-0.605	-0.111	0.035
	R^2	0.998	0.994	0.998	0.985	0.994	0.992

$\overline{SSDE}$, mean size-specific dose estimate; $SSDE_{center}$, size-specific dose estimate in the central slice of scan range; C, chest; A, abdomen; P, pelvis; CA, chest and abdomen; AP, abdomen and pelvis; CAP, chest, abdomen, and pelvis.

and pelvis, when D_w profiles within these three regions are considered separately. The attenuation differences between tissues like liver, stomach and intestines, mainly occur around the central region of the abdomen. Therefore, in this region, the location and the value of $SSDE_{center}$ becomes slightly more critical with respect to $\overline{SSDE}$. However, this is not the case for chest and pelvis regions where the main difference in D_w is governed by the slices beyond the center; i.e., the variations between consecutive slices corresponding to the central region are negligible, compared with the abdomen. This may help to understand the RMSD results of the three body regions, where the largest differences between the $\overline{SSDE}$ and $SSDE_{center}$ take place in the abdomen, regardless of age (Table 4). Regression analysis between $\overline{SSDE}$ and $SSDE_{center}$ also indicates that, when compared with chest and pelvis, abdomen has lower R^2 values due to the same reason (Table 5).

For the chest-abdomen subregion, $\overline{SSDE}$ values were observed to exceed $SSDE_{center}$ values for the first two age groups. This may be due to the position of central slice which is located around the area beneath the diaphragm and above the intestines, thus having a higher D_w compared with $\overline{D}_w$ along the chest-abdomen and resulting in lower $SSDE_{center}$. However, for the third group this is not the case. $\overline{SSDE}$ and $SSDE_{center}$ results were observed to exceed each other almost in equal proportion among the patients. This behavior can be interpreted with the possible changes in the location of central slice, therefore in $SSDE_{center}$ information, due to variable longitudinal length of the abdomen coming out from a broad scale of patient height. This interpretation may also explain the relatively weaker correlation between the $\overline{SSDE}$ and $SSDE_{center}$ (R^2=0.973) values for this group; though it is statistically acceptable (Table 5). On the other hand, for the abdomen-pelvis region where the $SSDE_{center}$ result comes from the intestinal area for all patient groups, D_w profile of the pelvis region plays an important role on the difference between $\overline{SSDE}$ and $SSDE_{center}$ for which $\overline{SSDE}$ was observed to exceed $SSDE_{center}$ among all groups. Here, the difference between $\overline{D}_w$ and the central D_w is mostly governed by the pelvis for the third group patients; therefore yielding to a considerable difference of 11% between the mean SSDE and $SSDE_{center}$ values. In contrast, RMSD results for the entire CAP region indicate that the largest relative difference is observed in the first group with 5.6%. As mentioned before, abdomen is the region with the highest D_w values for this group, and it is slightly more critical to correspond $\overline{D}_w$ of the entire CAP region. For this reason, it is reasonable to assume a larger difference between $SSDE_{center}$ and $\overline{SSDE}$ information compared with the other groups of patients. On the other hand, the degree of correlation is weakest for the third group, again owing to the variations in the location of central slice.

$\overline{D}_w$ results along the scan ranges were recorded between 14.6 cm (pelvis region of group 1) and 23.3 cm (pelvis region of group 3) (Table 2). In addition, it was clearly observed that $\overline{SSDE}$ values are approximately twice the $CTDI_{vol}$ at every scan range and patient group. For example, in the CAP region, $\overline{SSDE}$ is 2.1 times, 1.9 times and 1.6 times larger than $CTDI_{vol}$ with respect to patient groups ranging from younger to older (Table 3). An important point of conclusion which stands out is that the $\overline{D}_w$ values are compatible in size with the head phantom which is 16 cm in diameter, rather than the body phantom which is 32 cm in diameter. However, $CTDI_{vol}$ information displayed

both on the console and the exam specific dose report is based on the body phantom. Besides, it should be noted that even if a head phantom is used, it does not account for the changes in size, observed along a single patient or among different patients.

There are limitations to this study related to the physical origin of $CTDI_{vol}$. For example, for one complete rotation of the x-ray tube in a multislice CT scanner, all slices do not experience the same amount of absorbed dose due to radiation scatter inside the medium. Maximum dose is experienced by the central slices, while it diminishes towards the edges. $CTDI_{vol}$ is an average dose information mainly for the central section of this profile. This makes it problematic to use the central dose value for the entire scan range and assign SSDE values towards the edges. Although SSDE is the most reasonable patient-specific absorbed dose approximation yet, this issue might be addressed in future studies for more accuracy.

In conclusion, we focused on the validity of $SSDE_{center}$ on pediatric patients of different age groups and showed that differences between $SSDE_{center}$ and $\overline{SSDE}$ are similar with respect to patient age in general. Therefore, one can use the $SSDE_{center}$ method and estimate the mean error as the average value determined over all patients, regardless of age. Nevertheless, for the abdomen and pelvis scans of 11–16 years age group one might keep in mind that the error margin is larger depending on patient age and anatomy. We propose that CT manufacturers should consider to regulate their dose reports to include $\overline{SSDE}$ information, since it offers more realistic results than $CTDI_{vol}$ based on the absorbed dose. In the absence of $\overline{SSDE}$ information, $SSDE_{center}$ could be a reasonable and easily applicable method in clinical practice. Clinical user needs to select the central slice of the axial scan range and draw A_{ROI} so as to cover the patient cross-section. Area of the A_{ROI} and the mean HU number of pixels remaining inside need to be recorded in order to determine A_w via Eq. 2a. Consecutive execution of Eq. 2b and Eq. 3 will afterwards lead to the determination of f D_w to be used in Eq. 5 together with the $\overline{CTDI}_{vol}$ information for the determination of $SSDE_{center}$ value of scan.

Conflict of interest disclosure

The authors declared no conflicts of interest.

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