Size-Specific Dose Estimates Based on Water-Equivalent Diameter and Effective Diameter in Computed Tomography Coronary Angiography

Authors' Contribution:
Study Design A
Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
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Background: To determine the difference in size-specific dose estimates (SSDEs), separately based on effective diameter (deff) and water equivalent diameter (dw) of the central slice of the scan range in computed tomography coronary angiography (CTCA).

Material/Methods: There were 134 patients who underwent CTCA examination, were electronically retrieved. SSDEs ($SSDE_{deff}$ and $SSDE_{dw}$) were calculated using 2 approaches: deff and dw. The median SSDEs and mean absolute relative difference of SSDEs were calculated. Linear regression model was used to assess the absolute relative difference of SSDEs based on the ratio of deff to dw.

Results: The median values of $SSDE_{deff}$ and $SSDE_{dw}$ were 18.26 mGy and 20.56 mGy, respectively ($P<0.01$). The former was about 10.08% smaller than the latter. The mean absolute relative difference of SSDEs was 10.48%, ranging from 0.33% to 24.16%. A considerably positive correlation was found between the absolute relative difference of SSDEs and the ratio of deff to dw ($R^2=0.9561$, r=0.979, $P<0.01$).

Conclusions: The value of $SSDE_{deff}$ was smaller by an average of about 10.08% than $SSDE_{dw}$ in CTCA, and the absolute relative difference increased linearly with the ratio of effective diameter to water equivalent diameter.

MeSH Keywords: Body Size • Coronary Angiography • Radiation Dosage • Tomography Scanners, X-Ray Computed

Abbreviations: $CTDI_{vol}$ – volume CT dose index; **DLP** – dose length product; **deff** – effective diameter; **dw** – water equivalent diameter; f – size-dependent conversion factor; **SSDE** – size-specific dose estimate; $SSDE_{deff}$ – size-specific dose estimate based on deff; $SSDE_{dw}$ – size-specific dose estimate based on dw; **AP** – anteroposterior; **LAT** – lateral

Full-text PDF: https://www.medscimonit.com/abstract/index/idArt/917980

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Background

Computed tomography (CT) volume index ($CTDI_{vol}$) and dose length product (DLP) are widely used in clinical practice to quantify radiation dose from CT scan and they help in performing quality assurance procedures [1–4]. $CTDI_{vol}$ measured in mGy is routinely estimated by using standard 16 cm or 32 cm diameter polymethyl methacrylate cylinder phantoms and is susceptible to scan parameters, such as kV, mAs, pitch, collimator, bowtie filter, and so on. DLP measured in mGy·cm is the product of $CTDI_{vol}$ multiplied by the scan range, and it is the metric of total radiation dose output from a given CT scan. Presently, $CTDI_{vol}$ and DLP are displayed on CT units for each scan [5]. Although these metrics are tagged to individual examination, they do not take into account the correlated factors of patients undergoing CT examination [5,6–8]. Therefore, these 2 metrics represent the radiation dose output of CT scanner with the given scan details, but not the radiation dose absorbed by the patient [5,9–11].

On the basis of a large number of studies on $CTDI_{vol}$ normalized to patient's geometric size and different attenuations of various substances, the American Society of Physicists in Medicine (AAPM) Report 204 and 220 introduced the concept of size-specific dose estimate (SSDE), which is the product of $CTDI_{vol}$ and size-dependent conversion factor (f) [12,13]. The SSDE corrects the phantom-derived scanner-indicated $CTDI_{vol}$ according to the patient size and more accurately and reasonably estimate the radiation dose at the center of the scan range [10,11].

SSDE metrics were classified as $SSDE_{deff}$ based on effective diameter (deff) and $SSDE_{dw}$ based on water equivalent diameter (dw). A recent series of articles reported radiation dose to investigate the differences between $SSDE_{deff}$ and $SSDE_{dw}$ in CT examinations of the torso, such as chest, abdomen, and pelvis [14–16]. These studies demonstrated that $SSDE_{deff}$ underestimated radiation dose in chest compared to $SSDE_{dw}$, on the contrary, $SSDE_{deff}$ was generally greater than $SSDE_{dw}$ in abdomen and pelvis. Due to the different anatomic section, scan range and required contrast medium in CT coronary angiography (CTCA), the discrepancy of $SSDE_{deff}$ and $SSDE_{dw}$ in the aforementioned studies may not account for that of CTCA. Furthermore, to the best of our knowledge, no report on the 2 SSDE metrics in CTCA has been published so far. The purpose of this work was to assess and compare individual radiation dose metrics of $SSDE_{deff}$ and $SSDE_{dw}$ at the mid-point of the scan range from patients who underwent CTCA.

Material and Methods

Patient population

This retrospective study was approved by the institutional Ethics Committee and written informed consent was waived. Initially, 162 patients who underwent CTCA examination were electronically queried in Picture Archive and Communication System (PACS) of one institution, Zhejiang Provincial People's Hospital. Patients who had known allergic reaction to iodine contrast medium, severe renal failure, suspected and known pregnancy were excluded. All patients had clinically indicated or diagnosed coronary artery disease (CAD). There were 28 patients excluded because they had stent implant, mechanical valve replacement surgery, metal bodies on the skin, and truncated images which may result in potential inaccuracy of radiation dose exposed to patients (in $SSDE_{dw}$). Finally, for the period between January 2018 and June 2018, a total of 134 patients were enrolled in this retrospective study. There were 91 males and 43 females, their mean age was 59.67±11.70 years (range 30 to 90 years), their mean weight was 64.72±9.54 kg (range 44 kg to 90 kg) and their body mass index (BMI) was 23.79±2.57 kg/m^2 (range 17.14 kg/m^2 to 29.90 kg/m^2).

Data acquisition

All patients with a heart rate (HR) <65 beats per minute underwent axial volume CT scan on 320-detector CT (Aquilion ONE, Toshiba Medical Systems, Otaware, Japan). All the examinations were performed within 1 beat acquisition with prospective electrocardiogram-gating. A breath-hold exercise was performed before diagnostic scan. The diagnostic exposure phase window was limited automatically to 70% to 80% of the R-R interval by the scanner on the basis of HR during a breath-hold exercise. The scan parameters were tube voltage 100 kVp to 120 kVp, tube current 400 mA to 550 mA, and rotation time 0.35 seconds per rotation. Tube voltage and current were manually adjusted by radiographer according to individual BMI and shape of the imaging region. The other key parameter was that the scan range matched the personal length along the z axis of the heart, corresponding to four options of 120 mm, 128 mm, 140 mm, and 160 mm. The images were reconstructed with soft tissue algorithm (FC43 kernel), a 512×512 matrix, 400×400 mm FOV, 5 mm of slice thickness, and 5 mm of slice interval. The reconstructed images were automatically transferred to PACS (Greenlander version 6.0, Mindray Healthcare, Shenzhen, China).

A manual trigger technique was used across all patients. A 30 mL saline solution was injected via an 18-gauge catheter placed in the antecubital vein at a rate of 6.0 mL/second to test the injection pressure. This facilitated the decrease of the risk of extravagated contrast medium during contrast

medium administration. A dose of 0.6 mL/kg contrast medium with an iodine concentration of 320 mg/mL was injected over 10 seconds using a dual power injection system. Injection of this iodine solution was followed by 20-mL diluted contrast medium with a ratio of 3 to 7 (contrast medium to saline solution) and 30 mL of flush saline solution at the same rate as the contrast medium.

Calculation of SSDE

Deff, as defined in AAPM 204, was the diameter of the maximal anteroposterior and later dimensions. Patient sizes of AP and LAT were manually measured on the central transverse image of the CTCA scan range. AP and LAT values were summed to obtain a single index [12], as follows:

$$deff = \sqrt{AP \times LAT} \qquad (1)$$

A semi-automated segmentation technique based on CT value threshold, filling holes, keeping largest and editing mask with Mimics software (version 17, Materialise Medical System, Belgium) was used to delineate the boundary of the transverse image out from the surrounding air and the table. The average CT value and total pixel numbers were automatically reported in the properties of the established mask to calculate dw of the axial image. In addition, lower attenuation region (Area$_{low}$) with CT value smaller than −600 HU and higher attenuation region (Area$_{high}$) with CT value greater than 200 HU, were segmented out from the transverse image, and the CT values of Signal$_{low}$ and Signal$_{high}$ corresponding to Area$_{low}$ and Area$_{high}$ were documented. The value of dw was calculated as [13];

$$d_W = 2\sqrt{\left(\frac{CT_{ROI}}{1000} + 1\right) \cdot \frac{A_{ROI}}{\pi}} \qquad (2)$$

Where CT_{ROI} and A_{ROI} are the average CT value and the area of the axial image at the central slice location of the scan range respectively. A_{ROI} was calculated as;

$$A_{ROI} = N \times A_{pixel} \qquad (3)$$

Where N is the sum of pixels on the axial image while A_{pixel} is the area per pixel in cm^2.

SSDEs (SSDE$_{deff}$ and SSDE$_{dw}$, respectively) were derived from both deff and dw. SSDE was calculated as;

$$\text{SSDE} = f \times \text{CTDI}_{vol} \qquad (4)$$

Where f is the size-dependent conversion factor to correct patient size in deff and dw, and are defined as f_{deff} and f_{dw}, respectively. CTDI$_{vol}$ reported by the scanner is the average CTDI$_{vol}$ across all slices of the scan range. Due to the tube voltage of 120 kV, f was calculated as [12];

$$f = 4.378094 \times exp\left(-0.04331124 \times d\right) \qquad (5)$$

Where d is the value of deff or dw to express patient size in centimeter.

In this work, each scan protocol was conducted using standard 32 cm diameter polymethyl methacrylate cylinder phantoms to obtain the CTDI$_{vol}$ across all slices. According to the special approach for calculating SSDE, the data set was divided into group A and group B. In group A, 134 patients were included, and patient size was characterized by deff. SSDE was defined as SSDE$_{deff}$, which was calculated using f_{deff} at the central slice multiplied by CTDI$_{vol}$ value displayed on the radiation dose page. Similarly, in group B, 134 patients were included, and patient size was characterized by dw. SSDE was defined as SSDE$_{dw}$, which was calculated using f_{dw} at the central slice multiplied by CTDI$_{vol}$ value. To observe the homogeneity of the body phantom of 32 cm and actual body size, the difference of 32 cm and deff, 32 cm and dw Δ_d^{32} (cm), (32-cm versus deff, 32-cm versus dw) was calculated. The difference was defined as Δ_d^{32} (cm). The absolute relative difference, Er$_{ssde}$, between SSDE$_{deff}$ and SSDE$_{dw}$ was calculated to observe the accuracy of estimation dose. To study the change of Er$_{ssde}$ with dw, patients were split into 4 segments according to interquartile range of water equivalent across all patients. The 4 segments of patients were, dw-segment 1 for dw ≤23.82 cm, dw-segment 2 for 23.82 cm <dw ≤25.10 cm, dw-segment 3 for 25.10 cm <dw ≤26.31 cm, and dw-segment 4 for dw >26.31 cm.

Statistical analysis

All data were tested using Shapiro-Wilk test and Levene test. Numerical data with a normal distribution was reported as mean±standard deviation. Those with a skewed distribution were reported as median (P_{25}, P_{75}). Student's 2-tailed t-test was used to compare Δ_d^{32} (cm), body size, area, and signal, while Wilcoxon was performed for f, and SSDE. A broken line graph was used to illustrate the trend of Er$_{ssde}$ changing with dw. The difference of CTDI$_{vol}$, SSDE$_{deff}$, and SSDE$_{dw}$ was observed using Friedman test.

Pearson correlation test was performed for SSDE$_{dw}$ and dw, as well as for Er$_{ssde}$ and dw, while Spearman rank correlation test was carried out for SSDE$_{deff}$ and dw, as well as for Er$_{ssde}$ and Pro$_{size}$. Linear regression models were used to estimate the separate relationship of deff and dw, SSDE$_{deff}$ and SSDE$_{dw}$, Er$_{ssde}$ and the ratio of deff to dw (named as Pro$_{size}$). Multiple stepwise regression analysis was performed to observe the effect of Area$_{low}$, Area$_{high}$, Signal$_{low}$, and Signal$_{high}$ (independent variables) on SSDE$_{deff}$ and Er$_{ssde}$ (dependent variables), respectively. To assess the magnitude of variation explained by independent variable, the squared coefficients of determination (R^2) was calculated. A P-value of less than 0.5 was considered to

Table 1. Mean and standard deviation of the Δ_d^{32} (cm) and Body Size (cm), Median (P_{25}, P_{75}) of f and SSDE (mGy).

Approach	Δ_d^{32} (cm)	Body size (cm)	f	SSDE (mGy)
A	4.48±1.75	27.52±1.75	1.33 (1.26, 1.41)	18.26 (15.65, 21.72)
B	6.96±1.80	25.04±1.80	1.48 (1.40, 1.56)	20.56 (17.21, 24.00)
P	0.000*	0.000*	0.000**	0.000**

Approach A – size-specific dose estimate based on effective diameter; Approach B – size-specific dose estimate based on water equivalent diameter. Δ_d^{32} (cm) difference of phantom diameter and body size; f size-dependent conversion factor; SSDE size-specific dose estimate; * Student's *t*-test; ** Wilcoxon test.

indicate statistically significant difference. All statistical analyses were conducted using statistical software PASW 18.0 (IBM Corp. Armonk, NY, USA).

Results

A total of 134 axial images were measured in this work. There were 133 slices with deff smaller than 32 cm of body phantom, while 1 slice was higher than 32 cm of body phantom. All dw values were smaller than 32 cm. There was no slice with body size equal to 32 cm. All values of f_{deff} and f_{dw} were greater than 1. There was no slice with f less than or equal to 1.

As shown in Table 1, there was significant difference in Δ_d^{32}, body size and SSDE of the 2 groups. The average deff was about 9.99% higher in group A than dw in group B. The average $SSDE_{deff}$ was about 10.08% smaller than $SSDE_{dw}$.

The median (P_{25}, P_{75}) of CTDIvol, SSDEdeff and SSDEdw were 13.15 (interquartile range 11.48, 16.60) mGy, 18.26 (interquartile range 15.65, 21.72) mGy, and 20.56 (interquartile range 17.21, 24.00) mGy, respectively. $CTDI_{vol}$ was about 24.36% (range 8.15% to 39.69%) smaller than $SSDE_{deff}$, and about 32.09% (range 24.72% to 47.48%) smaller than $SSDE_{dw}$. $SSDE_{deff}$ was about 10.08% (range −2.89% to 24.19%) smaller than $SSDE_{dw}$. A significant difference was found in these 3 radiation metrics (χ^2=264.060, P<0.01). A representative case is shown in Figure 1.

As shown in Figure 2, deff was positively correlated with dw (R^2=0.6434, r=0.802, P<0.01), while $SSDE_{deff}$ was positively correlated with $SSDE_{dw}$ (R^2=0.9436, r=0.972, P<0.01). $Area_{low}$ and $Area_{high}$ were 170.28±45.35 cm^2 (range 68.59 to 326.75 cm^2), 74.16±11.64 cm^2 (range 45.06 to 100.78 cm^2), respectively and a significant difference was found between them (*t*=24.126, P<0.01). $Signal_{low}$ and $Signal_{high}$ were −889.56±75.58 HU (range −621.36 to −998.36 HU) and 407.19±37.32 HU (range 326.81 to 527.53 HU), respectively, and there was a significant difference between them (*t*=−170.699, P<0.01) as well. Multi stepwise regression analysis showed that $Signal_{high}$ (normalized β=−0.528) was independently and negatively associated with
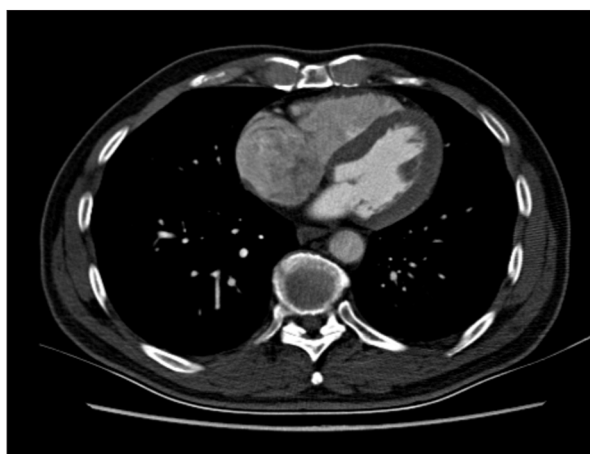

Figure 1. A 64-year-old male undergoing computed tomography coronary angiography (CTCA). His body mass index (BMI) was 22.49 kg/m^2. An image at the central location in the scan range. The anteroposterior (AP) and lateral (LAT) were 22.9 cm and 32.9 cm, respectively. The effective diameter (deff) was 27.5 cm. The size-dependent conversion factor (f_{deff}) was 1.33. The CT volume index ($CTDI_{vol}$) of this scan was 10.7 mGy. The size-specific dose estimate ($SSDE_{deff}$) was 14.26 mGy based on formula 4. The water equivalent diameter (dw) was 24.4 cm and the size-dependent conversion factor (f_{dw}) was 1.52. The size-specific dose estimate ($SSDE_{dw}$) was 16.30 mGy while $SSDE_{deff}$ was about 12.52% smaller than $SSDE_{dw}$.

$SSDE_{deff}$. $Area_{low}$, $Signal_{low}$ and $Area_{high}$ were not included in the regression equation.

There was a weak positive correlation between $SSDE_{deff}$ and dw (r=0.267, P=0.002), the same correlation level was found between $SSDE_{dw}$ and dw, however, it was not statistically significant (r=0.136, P=0.116).

The average of Er_{ssde} was 10.48±4.76%, ranging from 0.33% to 24.16%. There was a moderate negative correlation between Er_{ssde} and dw (r=−0.342, P<0.01). As shown in Figure 3, Er_{ssde} changed with dw. Between dw-segment 1 and dw-segment 4, Er_{ssde} declined from 11.52% down to 8.22%. There was
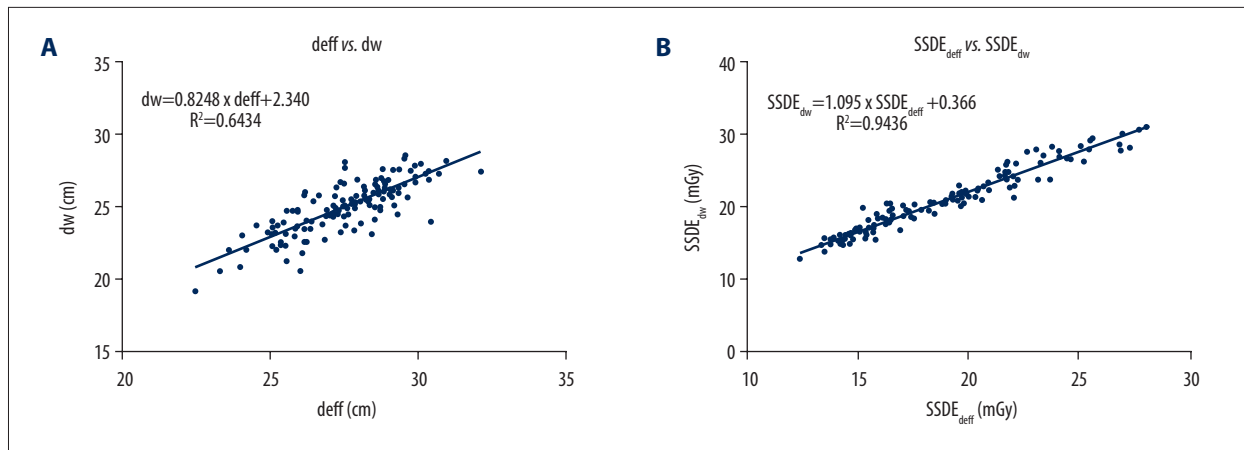
Figure 2. (**A**) Scatter plot representing relationship between deff and dw. There was a considerably positive correlation (Pearson analysis, $R^2=0.6434$, r=0.802, $P<0.01$). (**B**) Scatter plot representing relationship between $SSDE_{deff}$ and $SSDE_{dw}$. There was a considerably positive correlation (Spearman analysis, $R^2=0.9436$, r=0.972, $P<0.01$). dw – water equivalent diameter; deff – effective diameter; $SSDE_{dw}$ – size-specific dose estimate based on water equivalent diameter; $SSDE_{deff}$ – size-specific dose estimate based on effective diameter.
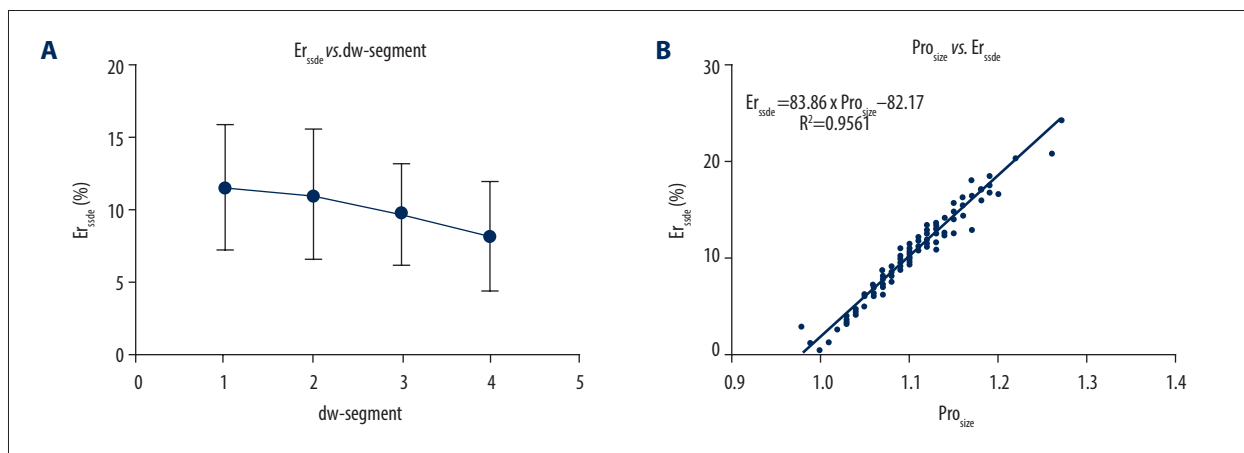

Figure 3. (**A**) Line chart representing the relationship between Er_{ssde} and dw segment. A decreasing trend of Er_{ssde} was illustrated with dw increasing. Er_{ssde} declined from 11.52% down to 8.22%. (**B**) Scatter plot representing relationship between Pro_{size} and Er_{ssde}. There was a considerable positive correlation ($R^2=0.9561$, r=0.979, $P<0.01$). Er_{ssde}, absolute relative difference of size-specific dose estimates based on effective diameter and water equivalent diameter; dw-segment, patients split according to interquartile range of water equivalent across all patients; dw-segment 1, patients with dw ≤23.82 cm; dw-segment 2, patients with 23.82 cm <dw ≤25.10 cm; dw-segment 3, patients with 25.10 cm <dw ≤26.31 cm; and dw-segment 4, patients with dw >26.31 cm. Pro_{size} – the ratio of effective diameter to water equivalent diameter.

a considerable positive correlation between Er_{ssde} and Pro_{size} ($R^2=0.9561$, r=0.979, $P<0.01$). With Pro_{size} as a dependent variable, $Area_{low}$, $Area_{high}$, $Signal_{low}$ and $Signal_{high}$ as independent variables, multiple stepwise regression analysis showed that $Area_{low}$ was independently and positively associated with Pro_{size} (normalized β=0.504, $P<0.01$), whereas $Signal_{low}$ was independently and negatively associated with Pro_{size} (normalized β=−0.461, $P<0.01$). Both $Area_{high}$ and $Signal_{high}$ were not included in the regression equation and had an insignificant influence on Er_{ssde}.

Discussion

Compared with SSDE, $CTDI_{vol}$ tends to underestimate radiation dose ranging from 14.29% to 36.46% in CT chest sans, especially for thin or pediatric patients [1,17]. Consistent with previous studies [1,17], the current findings revealed that $CTDI_{vol}$ in CTCA estimated patient dose to be smaller than 27.95% and 37.20% on average than $SSDE_{deff}$ and $SSDE_{dw}$, respectively. $CTDI_{vol}$ in torso is obtained on the basis of the standard phantom of 32 cm diameter. In contrast, the actual values of deff and dw in adult chest were almost smaller than 32 cm and

f was greater than 1. The difference between 32 cm and actual chest size might result in $CTDI_{vol}$ estimation inaccuracy. Thus, the standard 32 cm diameter polymethyl methacrylate cylinder phantom used to represent realistic adult chest to estimate radiation dose in chest CT examination is controversial [5,15,18,19]. So, instead of $CTDI_{vol}$, SSDE, which takes patient correlated factors into account, can be considered as a great positive step in the field of CT dose estimation.

Compared to $CTDI_{vol}$, $SSDE_{deff}$ has significantly improved the accuracy of dose estimation [20–22]. One of the advanced features of $SSDE_{deff}$ lies in its simplicity and efficiency. AP and LAT required by deff can be easily obtained on a single axial image. However, in the anatomic region of the considerable x-ray attenuation inhomogeneity, $SSDE_{deff}$ may result in mis-estimated radiation dose, changing with tissues attenuation characteristics [11]. A recent series of studies revealed that $SSDE_{deff}$ estimated radiation dose was markedly smaller than actual patient chest absorbed dose [12,15,18]. The findings in the current study demonstrated that $SSDE_{deff}$ was different from $SSDE_{dw}$, with an average underestimation of 10.08% (range -2.89% to 24.19%) in CTCA. Chest is fully filled with air, which has extremely weak x-ray attenuation and much lower CT value than water. Therefore, these previous studies indicated that air was the primary factor affecting the estimation performance of $SSDE_{deff}$ in chest. Contrary to these studies, $Signal_{high}$, rather than $Area_{low}$, $Area_{high}$, and $Signal_{low}$, significantly affects the change of $SSDE_{deff}$ in CTCA, and a negative relationship was found between $Signal_{high}$ and $SSDE_{deff}$ in the current work. Thus, it would be theoretically expected that $SSDE_{deff}$ tends to get close and even equal to $SSDE_{dw}$, as $Signal_{high}$ decreases. However, intraluminal attenuation is required to meet diagnostic image quality in CTCA. The assumption that $SSDE_{deff}$ is equal to $SSDE_{dw}$ will not be established, and difference between them will be maintained in radiologic practice.

In this study, deff was not in accordance with dw. The x-ray attenuation of air, bony and enhanced structures was considerably different from that of water. The air decreased the attenuation of patient considerably, which mainly increased the geometrical dimension. On the contrary, high x-ray attenuation bony and enhanced structures mainly resulted in increased dw. However, $Area_{low}$ was significantly greater than $Area_{high}$, while in terms of CT value, air was at the bottom level in all tissues of the scan region of CTCA. Thus, air is significantly different from bony and is enhanced in area and x-ray attenuation. It may result in 64.34% of variation in dw (R^2=0.6434) explained by deff and difference between $SSDE_{deff}$ and $SSDE_{dw}$.

Increase in both $SSDE_{deff}$ and $SSDE_{dw}$ with patient dw size was observed in this work. This was expected due to adjustment of scan parameters for the inter-patient acceptable diagnostic image quality. Large patient size indicates larger geometrical dimension and higher x-ray attenuation, which can cause increased visual noise, obscured anatomic details and decreased contrast to noise ratio (CNR) [23]. Thus, to maintain a comparable diagnostic image quality, larger patients are required to use more x-photon than small patients. It is noteworthy that there was no statistical significance in correlation of $SSDE_{dw}$ and dw. It was considered that normalized $CTDI_{vol}$ using dw, which combined geometrical dimension with x-ray attenuation [10,11,16], resulted in $SSDE_{dw}$ with less variation compared to $SSDE_{deff}$ across all patients. Thus, $SSDE_{dw}$ was considered be a more reasonable metric to establish CT diagnostic reference level, from which patients would benefit more. On the other hand, according to the inverse exponential correlation of f and body size [12,13], small patients would be exposed to higher SSDE, large patients would be exposed to lower SSDE with the constant $CTDI_{vol}$. The effect would be the same for both $SSDE_{deff}$ and $SSDE_{dw}$.

It was observed that there was an average Er_{ssde} of 10.48±4.76% between $SSDE_{deff}$ and $SSDE_{dw}$, ranging from 0.33% to 24.16%. Er_{ssde} decreased with increasing dw. It would be expected that $SSDE_{deff}$ was very close to $SSDE_{dw}$ for larger patient. When the patient size increased beyond a certain value, $SSDE_{deff}$ would equal to $SSDE_{dw}$. On the contrary, when patient size shifted to the smaller end, Er_{ssde} became greater, and $SSDE_{deff}$ would considerably move away from $SSDE_{dw}$, which is explained by the negative exponential correlation of f and body size [12,13]. Based on the aforementioned observation no significant correlation was found between $SSDE_{dw}$ and dw, the analysis using $SSDE_{dw}$ seemed to be more beneficial for thin patients in CTCA, although $SSDE_{deff}$ and $SSDE_{dw}$ provided the radiation dose measurements. The metric of $SSDE_{deff}$ is suitable for estimating larger patient radiation dose in CTCA.

To further explore the causes of estimation Er_{ssde}, multiple stepwise regression analysis revealed that low attenuation tissues had a noticeable impact on Pro_{size}. Combined with the positive correlation of Pro_{size} and Er_{ssde}, it was considered that $Area_{low}$ may result in the variation of Er_{ssde}, which indicated that $SSDE_{deff}$ was comparable to $SSDE_{dw}$ with decreasing $Area_{low}$, and $Signal_{low}$ may result in increased Er_{ssde} to a certain extent with decreasing $Signal_{low}$, which indicated the shift of $SSDE_{deff}$ from $SSDE_{dw}$. In clinical practice, $Area_{low}$ may vary considerably from patient to patient, generally $Signal_{low}$ is maintained at a relatively constant level. In fact, $Area_{low}$ would be the critical variable impacting on Er_{ssde}. With respect to high attenuation tissues, both $Area_{high}$ and $Signal_{high}$ did not impact on Pro_{size} significantly, and their impact on Er_{ssde} was negligible. It was assumed that high attenuation tissues would theoretically become the key variables to impact the Pro_{size} and Er_{ssde} with increasing $Area_{high}$ and $Signal_{high}$. As a matter of fact, $Area_{high}$ changed within a relative narrower range from 45.06 cm² to 100.78 cm² contrast to the variation range of $Area_{low}$ over all

the patients in this work, and CT value of 300 HU was enough to ensure that the lesion could be detected efficiently, over enhanced intraluminal attenuation would cause inverse effect to obscure diagnostic performance of CCTA [24]. Thus, the probability of high attenuation tissues to significantly change Pro_{size} and Er_{ssde} would be low in CTCA.

This study has several limitations. Firstly, the axial scan mode of fixed tube current was used to perform CTCA, which may limit the generalizability of results to the mode of automatic tube current modulation. To the best of our knowledge, the study, however, is the first report on differences between $SSDE_{deff}$ and $SSDE_{dw}$ in CTCA. Secondly, the data used in this study was retrieved from one institution. Although standard operation procedure can be put into radiologic practice regardless of experiment and expertise variation of technologist in individual institution, it may be necessary that the suggestions of this study would be reconfirmed using multicenter dataset in future. Thirdly, dw was automatically calculated, in contrast, measurement of deff was performed manually. Thus, individual approach might result in discrepancy of body size measurements from actual values which may partially cause a bias in retrospective CT radiation dose analyses.

Conclusions

In conclusion, although both $SSDE_{dw}$ and $SSDE_{deff}$ can be used as the radiation dose metrics in CTCA for adult patients, $SSDE_{deff}$ underestimates the radiation dose by an average of about 10.08% compared to $SSDE_{dw}$. The ratio of effective diameter to water equivalent diameter, especially low attenuation details in terms of area and signal intensity, had a significant effect on Er_{ssde} between $SSDE_{dw}$ and $SSDE_{deff}$. Therefore, $SSDE_{dw}$, rather than $SSDE_{deff}$, is a relatively reasonable metric to accurately determine the radiation dose absorbed by patients in CTCA and was recommended to implement into clinical practices.

Conflict of interest

None.

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