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# Comparative Study of Volume Computed Tomography Dose Index and Size-Specific Dose Estimate Head in Computed Tomography Examination for Adult Patients Based on the Mode of Automatic Tube Current Modulation

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Data Collection B  
Statistical Analysis C  
Data Interpretation D  
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**Background:** The aim of this study was to compare the metrics of volume computed tomography index ( $CTDI_{vol}$ ) and size-specific dose estimate (SSDE), and quantify the differences in head CT examinations of adult patients.





**Material/Methods:** A total of 157 patients underwent head CT examination were enrolled in this retrospective study. Pearson correlation analysis and linear regression correlation analysis were performed to observe the correlation between the dose metrics of  $CTDI_{vol}$  and SSDEaver versus tube current product (mAs) and water equivalent diameter (WED). Correlated factors of  $CTDI_{vol}$  and SSDEaver were analyzed by multivariate linear stepwise regression analysis.

**Results:** A sum of 4239 data settings were measured: slices with WED >16 cm was 71.05%, and the slices with  $f < 1$  was 72.64%. The average value of the absolute difference between WED and the diameter of AAPM head phantom was  $2.24 \pm 1.42$  cm. Statistically significant difference was found between the values of  $CTDI_{vol}$  and SSDEaver ( $P=0.000$ ). The dispersion degree of the  $CTDI_{vol}$  values was greater than that of SSDEaver. Strong positive correlation was shown between  $CTDI_{vol}$  and mAs ( $P=0.000$ ), as well as  $CTDI_{vol}$  and WED ( $P=0.000$ ). Strong positive correlation was shown between SSDEaver and mAs ( $P=0.000$ ), and moderate correlation for SSDEaver and WED ( $P=0.000$ ). Both the metrics of mAs and WED were included in the multivariate linear stepwise regression equation to observe the effect of related factors on the value of SSDEaver.

**Conclusions:** SSDEaver with better representative can reproduce the radiation dosage of the specific adult patients in head CT examination.

**MeSH Keywords:** Colonography, Computed Tomographic • Head • X-Rays

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## Background

With the increasing clinical use of computed tomography (CT) examinations, the radiation dose problems that accompany the benefits are receiving more and more attention and are also hot spots for clinical studies. At present, the volume CT dose index ( $CTDI_{vol}$ ) and the dose length product (DLP) are the most commonly used indexes for estimating radiation dose of CT examination. The  $CTDI_{vol}$  is calculated based on standard methyl methacrylate phantom with a diameter of 16 cm or 32 cm and represents the average radiation dose (mGy) within the scanning volume range. DLP is the product of  $CTDI_{vol}$  and scanning range (mGy-cm). Therefore, neither of them can accurately reflect the size of the patient, and there is a great uncertainty in the estimation of radiation dose absorbed by the patient.

In 2011 and 2014, the American Association of Physicists in Medicine (AAPM) issued a report that introduced effective diameter (ED) and water equivalent diameter (WED) to calibrate  $CTDI_{vol}$  for size-specific dose estimate (SSDE) of patients undergoing CT examination, which made up for the defect that  $CTDI_{vol}$  did not take into account of the influencing factors of a patient's radiation dose exposure estimation [1,2], and is currently a more reasonable metric parameter to estimate the radiation dose of a CT examination for a patient, and has begun to be applied to monitor the radiation dose and to affect quality control for a tested population [3–6]. Recent phantom experiments and clinical preliminary studies on abdominal CT examinations have shown that there is a difference in the estimated radiation dose of CT examination between SSDE and  $CTDI_{vol}$  [6,7–10], however, for comparing the difference in estimating the radiation dose of head CT between the 2 methods, the scanning protocol simulated by phantom experiment is not in accordance with the clinical practice [11]. Clinical study is based on the fixed tube current scanning mode rather than the current most commonly used automatic tube current modulation (ATCM) [12]. The purpose of this study was to compare the values of  $SSDE_{aver}$  and  $CTDI_{vol}$  in consecutive axial head CT scan in ATCM mode and quantify the difference between the 2 methods.

## Material and Methods

### Clinical data

A total of 186 patients undergoing head CT scan from April 2017 to May 2017 were retrospectively collected. The inclusion criteria were as follows: 1) the patient was diagnosed with head disease in clinic, and 2) the patient was older than 6 years of age. The exclusion criteria were as follows: 1) the patient underwent head CT scan in spiral scanning mode; 2) the patient had intracranial metal implant after intracranial aneurysm

clipping, intracranial stent implantation, or skull defect repair; 3) the patient had metal foreign bodies on body surface; and 4) the patient had poor cooperation during examination. A total of 157 patients were enrolled in this study, including 75 males and 82 females, the patients age ranged from 15 to 87 years, with a median age of 39 years.

### Imaging protocol

Siemens SOMATOM Definition AS 64-slice spiral CT was used. The patient was placed in a supine position, head first, and the positioning images of lateral scanning were acquired. The glabellomeatal line was used as the scan baseline. The scanning range was from the first cervical vertebra to the skull base. Scanning parameters: consecutive axial scan mode, tube voltage 120 kVp, the CARE Dose 4D technology was used, the mass reference mAs was 400 mAs, detector collimation 128×0.6 mm, acquisition matrix 512×512, reconstruction FOV 300×300 mm; source image slice thickness 0.6 mm, inter-slice spacing 0.6 mm; reformation image slice thickness 5 mm, inter-slice spacing 5 mm. A head phantom with a diameter of 16 cm was selectively used in all patients for the device to automatically calculate the  $CTDI_{vol}$  of the CT scan.

### Data measurement and calculation

After the scan was done, the images and the dose report generated by the device were automatically transmitted to the PACS (picture archiving and communication system). The  $CTDI_{vol}$  value of each patient was recorded according to AAPM Reports 204/220 [1,2]. The elliptical region of interest (ROI) including all the anatomical structures of the cross-sectional images was used to measure the CT values (CTROI, HU) of images of all slices, and the ROI area ( $A_{ROI}$ ,  $cm^2$ ) was recorded.  $CTDI_{vol}$  was standardized with reference to mAs in each slice, and the nominal  $CTDI_{vol}$  in all slices was calculated. The WED of each slice and the corresponding size-dependent conversion factor (f) were calculated, and the SSDE was calculated. Meanwhile, the average SSDE ( $SSDE_{aver}$ ) of the scanning volume was calculated. The calculation method was referred to AAPM Reports 204/220 [1,2], and the formula is as follows:  $CTDI_{vol}(s)$  in Formula (2) is the slice  $CTDI_{vol}$ ,  $CTDI_{vol}$  is average  $CTDI_{vol}$  of the scanning volume, mAs(s) is the slice mAs, and mAs(a) is the average mAs of the scanning volume. The f in Formula (3) is the size-dependent conversion factor corresponding to the water equivalent diameter of the slice.  $SSDE(s)$  in Formula (4) is slice SSDE.  $SSDE_{aver}$  in Equation (5) is the average SSDE of the scanning volume, and N is the total number of slices of the scanning volume. To compare the differences in estimated radiation dose, the data were divided into 2 groups:  $CTDI_{vol}$  was used for radiation dose estimation in Group A;  $SSDE_{aver}$  was used for radiation dose estimation in Group B. (Table 1.)

**Table 1.** The calculation method and the formula for average SSDE.

|   |
|---|
| $D_w = 2 \sqrt{\left( \frac{CT_{ROI}}{1000} + 1 \right) \cdot \frac{A_{ROI}}{\pi}} \quad (1)$ |
| $CTDI_{vol}(s) = \frac{mAs(s)}{mAs(a)} \cdot CTDI_{vo} \quad (2)$                             |
| $f = 1.874799 \times \exp(-0.03871313 \times D_w) \quad (3)$                                  |
| $SSDE(s) = f \cdot CTDI_{vol}(s) \quad (4)$   |
| $SSDE_{aver} = \frac{\sum_{s=1}^N SSDE(s)}{N} \quad (5)$                                      |

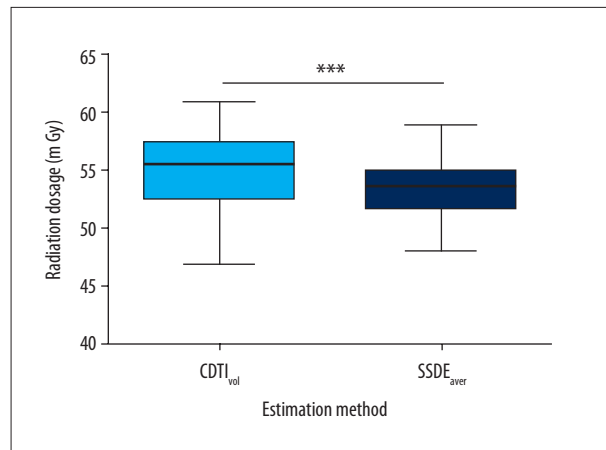
### Statistical analysis

Data analysis was performed using PASW 18.0 statistical package. All data were tested using K-S normality test and Levene's test for homogeneity of variance. Measurement data that corresponded to normal distribution were expressed as  $\bar{x} \pm s$ , and paired sample *t*-test was used; Pearson correlation analysis was used for correlation analysis of data with a bivariate normal distribution and the degree of correlation was analyzed using least squares linear regression analysis; multivariate correlation analysis was performed using multivariate stepwise linear regression analysis; the standard deviations, coefficients of variation, full ranges and interquartile ranges of  $CTDI_{vol}$  and  $SSDE_{aver}$  were respectively calculated to observe the dispersion degrees, and the box plot graph was made for the numerical distribution of  $CTDI_{vol}$  and  $SSDE_{aver}$ . A *P* value of  $<0.05$  was considered statistically significant.

## Results

### WED and *f*

The data of a total of 4239 slices were obtained from 157 patients. The slices of WED=16 cm accounted for 7.43% (315/4239), the slices of WED <16 cm accounted for 21.51% (912/4239), and the slices of WED >16 cm accounted for 71.05% (3012/4239). The WED was 5.6–20.0 cm, with an average of  $16.84 \pm 2.39$  cm, the absolute difference between WED and the diameter of AAPM head phantom (16 cm) was 0.00–10.4 cm, with an average absolute difference of  $2.24 \pm 1.42$  cm. The relative difference was 0.00–65.00%, with an average relative difference of  $14.18 \pm 8.84\%$ . The slices with  $f=1$  accounted for 20.29% (86/4239), the slices with  $f > 1$  accounted for 25.34% (1074/4239), and the slices with  $f < 1$  accounted for 72.64% (3079/4239).



**Figure 1.** Box plot graph: the distributions of estimated doses of  $CTDI_{vol}$  and  $SSDE_{aver}$ . The median, maximum value, minimum value, and interquartile range are marked. The  $CTDI_{vol}$  estimated doses had a greater degree of variation and the distribution of  $SSDE_{aver}$  estimated doses were more concentrated. \*\*\*  $P < 0.001$ .  $CTDI_{vol}$  – computed tomography dose index volume;  $SSDE_{aver}$  – size-specific dose estimate average.

### $CTDI_{vol}$ and $SSDE_{aver}$

A total of 4239  $SSDE(s)$  values were obtained from all patients.  $CTDI_{vol}$  value was higher than  $SSDE_{aver}$  value in 136 patients and was lower than  $SSDE_{aver}$  value in 20 patients, and both estimated dose values were equal in only 1 patient. The WED increased by about 5.25% compared with the phantom diameter of 16 cm, resulting in an increase in  $CTDI_{vol}$  value by about 2.99% compared to  $SSDE_{aver}$  value. The average  $CTDI_{vol}$  and  $SSDE_{aver}$  values were  $55.10 \pm 3.06$  mGy and  $53.50 \pm 2.29$  mGy, respectively, the difference was statistically significant ( $t=15.54$ ,  $P=0.000$ ). The distribution range of  $CTDI_{vol}$  values was wider and covered that of  $SSDE_{aver}$  values, as shown in Figure 1. The  $SSDE_{aver}$  had a smaller degree of dispersion, and the standard deviation, coefficient of variation, full range, and interquartile range for measuring the degree of dispersion were less than those of  $CTDI_{vol}$ , as shown in Table 2.

### Influencing factors of $CTDI_{vol}$ and $SSDE_{aver}$

Pearson correlation analysis showed that  $CTDI_{vol}$  was strongly positively correlated with both the average mAs of the scanning volume and WED ( $r=0.999$ ,  $0.650$ ,  $P=0.000$ ), and the correlation degrees are shown in Figure 2. Multiple stepwise linear regression analysis of influencing factors of  $CTDI_{vol}$  showed that WED did not enter the regression equation, only mAs had a significant effect on  $CTDI_{vol}$ , and the regression equation was  $CTDI_{vol} = 0.087 + 0.160 \times mAs$ .  $SSDE_{aver}$  had a strong positive correlation with the average mAs of the scanning volume ( $r=0.930$ ,  $P=0.000$ ) and a weak positive correlation with WED ( $r=0.35$ ,

**Table 2.** Comparison of the dispersion degree between  $CTDI_{vol}$  and  $SSDE_{aver}$ .

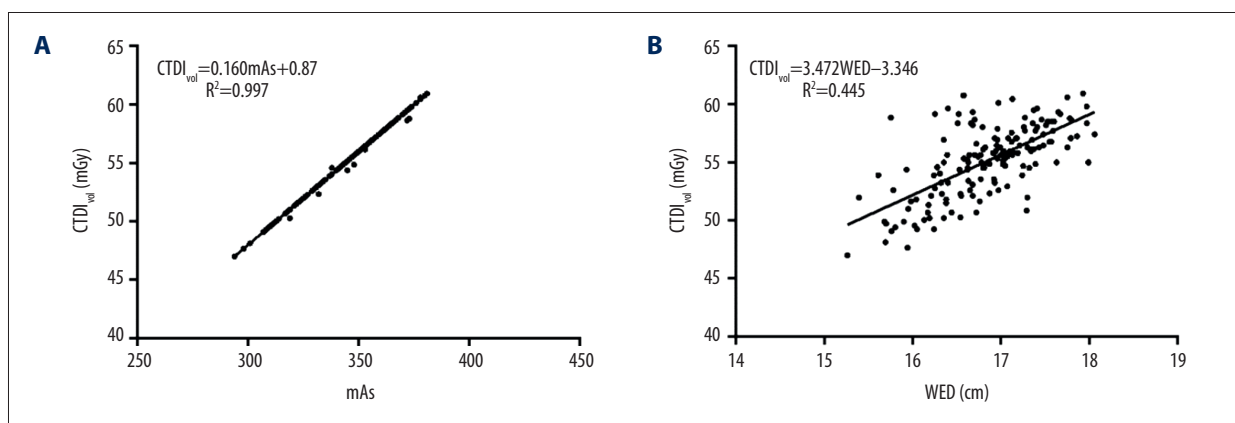
| Parameters                   | $CTDI_{vol}$ | $SSDE_{aver}$ | P value |
|------------------------------|--------------|---------------|---------|
| Standard deviation (mGy)     | 3.06         | 2.29          | 0.000   |
| Coefficient of variation (%) | 5.55         | 4.28          |         |
| Full range (mGy)             | 13.92        | 11.07         |         |
| Interquartile range (mGy)    | 4.48         | 3.03          |         |

$P=0.000$ ), and the correlation degrees are shown in Figure 3. Multiple stepwise linear regression analysis of influencing factors of  $SSDE_{aver}$  showed that both mAs and WED had

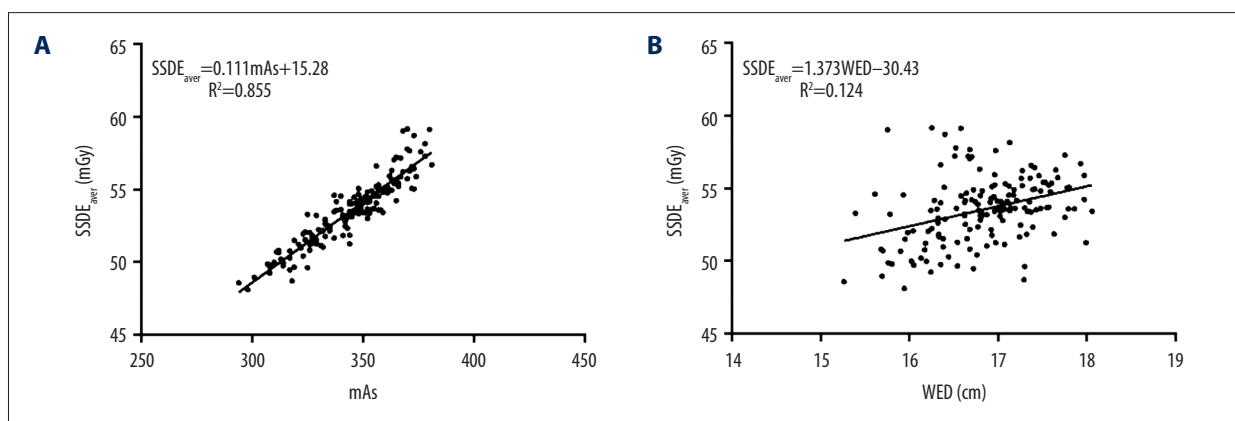
significant effects on  $SSDE_{aver}$ , and the regression equation was  $SSDE_{aver}=34.004-0.151 \times mAs-1.936 \times WED$ .

### Discussion

CT dose indexes include 3 parameters:  $CTDI_{100}$ , weighted  $CTDI$ , and  $CTDI_{vol}$ .  $CTDI_{vol}$  represents the average radiation dose of a standard phantom under a given scan parameter, and is highly susceptible to the scanning protocol. DLP is calculated based on the  $CTDI_{vol}$ , which is the product of the  $CTDI_{vol}$  and the scan range length. It is also the radiation dose index that reflects the changes in scanning parameters. Therefore, both  $CTDI_{vol}$  and DLP are based on the quality assurance of the phantom and do not reflect the size and tissue attenuation information of the patient. However, the size and tissue attenuation are closely related to the radiation dose absorbed by the



**Figure 2.** (A, B) Scatter diagram with fitting straight line showed correlations of  $CTDI_{vol}$  with the average mAs of the scanning volume and WED. The data of both groups were analyzed using least-squares linear regression analysis, and the linear regression equations and decision coefficients were labeled.  $CTDI_{vol}$  – computed tomography dose index volume; WED – water equivalent diameter.



**Figure 3.** (A, B) Fitting straight line showed correlations of  $SSDE_{aver}$  with the average mAs of the scanning volume and WED. The data of both groups were analyzed using least-squares linear regression analysis, and the linear regression equations and decision coefficients were labeled.  $SSDE_{aver}$  – size-specific dose estimate average; WED – water equivalent diameter.

patient. SSDE uses  $f$  to standardize  $CTDI_{vol}$ , overcoming the defect that  $CTDI_{vol}$  cannot reflect the specific body size of the patient. In addition to the geometric shape of the patient and tissue attenuation at the scan location,  $f$  is also related to the corresponding phantom selected by the scanning protocol. In this study, the selection of WED-based  $f$  was proposed by the AAPM Report 220 [2], and the  $CTDI_{vol}$  was calculated using the head phantom with a diameter of 16 cm as a reference. The WED assumes that the human body is composed of elliptical cross-sections and can be represented by a cylindrical water phantom with x-ray attenuation equivalent to that of human body. The cross-sectional area of the phantom represents the geometric size of the patient and the CT value represents the average attenuation of the tissue structure. Therefore,  $f$  based on the geometric shape and tissue attenuation can more accurately estimate the radiation dose of the patient.

Our results showed that only 7.34% WED had the same diameter as the phantom, WED of most slices was  $>16$  cm, and the average relative difference between WED of all slices and 16 cm was 14.18%. The reason for this may be that the geometric size of the head is not equivalent to the diameter of the phantom, and meanwhile the homogenous structure and consistent attenuation of the phantom cannot reflect the anatomical characteristics of the tissue structure such as unequal distribution and inconsistent attenuation. Thus, even if the geometric size is equivalent, the use of the phantom with homogeneous structure to represent the adult head still has greater uncertainty,  $CTDI_{vol}$  characterization of the radiation dose in the patient will deviate from the actual value.

In our study,  $CTDI_{vol}$  estimated dose was higher than  $SSDE_{aver}$  estimated dose. In this regard, the number of slices with WED  $>16$  cm in the head was dominant, and corresponding calibration of the  $CTDI_{vol}$  base value by  $f < 1$  was the most important reason. From the formula (3) combined with the phantom diameter, the smaller the difference between the head WED and 16 cm, the closer to 1  $f$  is, and the  $CTDI_{vol}$  estimated dose gradually converges towards the  $SSDE_{aver}$  estimated dose. Therefore, based on the fact that the head WED is not consistent with the diameter of the phantom, the  $CTDI_{vol}$  value does not actually reflect the radiation dose of the patient. Comparison of the dispersion tendency between  $CTDI_{vol}$  and  $SSDE_{aver}$  showed that the dispersion degree of  $SSDE_{aver}$  was relatively small, and  $SSDE_{aver}$  had a better representation of radiation dose estimates.

This study showed that mAs had a better correlation with  $CTDI_{vol}$  and could explain 99.7% changes in  $CTDI_{vol}$ , suggesting that mAs is an important influencing factor of changes in  $CTDI_{vol}$ . Although WED was moderately correlated with  $CTDI_{vol}$  and this could explain the 44.5%  $CTDI_{vol}$  which was excluded by the regression model of  $CTDI_{vol}$  that was influenced by many factors. Therefore, the body size of the patient had no significant

effect on  $CTDI_{vol}$ . In contrast, the correlation and correlation degree between mAs and  $SSDE_{aver}$  were relatively low. The difference between the 2 methods was that  $CTDI_{vol}$  was calculated based on the standard water phantom which had a consistent attenuation and a constant diameter, and the estimated dose changes along with the scanning parameters, while  $SSDE_{aver}$  after calibration of  $CTDI_{vol}$  by  $f$  had considered the effects of scanning parameters and the size characteristics of patients on the radiation dose, and it made up for the shortcoming in geometric size that the diameter of standard phantom was a fixed value. At the same time, this more accurately reflects the properties of the human tissues as a heterogeneous structure through the measurement of CT value [12]. In addition, the automatic tube current modulation technique was used in this study. The output dose of the device was accompanied by a change in body size, which was the reason why the 2 estimation methods had different correlation with mAs [13].  $SSDE_{aver}$  multi-factor regression analysis model also showed that both the scanning parameters and the body size of the patient has a significant effect on  $SSDE_{aver}$ , and it can better reflect the changes in scanning parameters and specific body size of the patient. However, the result found in this study that  $SSDE_{aver}$  was affected by the body size was different from other results that found that the body SSDE is independent of the changes in body size [8], this may be related to the differences in the anatomical structures of the head and body and the attenuation properties of the corresponding tissues, among which the high attenuation characteristics of skull to x-ray may be the most important reason. In addition, ATCM can more effectively adjust the tube current output in the spiral scan mode, and the consecutive axial scan mode in this study completed the scanning of preset volume in the forms of slices, and the tube current output can only be adjusted between slices [8].

## Conclusions

In summary, although  $CTDI_{vol}$  only slightly overestimates the radiation dose, it does not consider the effects of patient factors on the radiation dose. While  $SSDE_{aver}$  simultaneously considers the scanning protocol and the effects of the geometric shape of the patient and tissue attenuation on the radiation dose and the estimated value has a smaller dispersion degree and is more representative and can characterize the radiation dose of patient with specific body size. However,  $SSDE_{aver}$  only characterizes the average radiation dose of the tissues in the scanning range, and the conversion of the effective dose requires further study [2]. The dose estimation of the exposed organ still requires calibration of  $SSDE_{aver}$  by the organ dose conversion factor [2,11,14].

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