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Consideration of the usefulness of a size-specific dose estimate in pediatric CT examination

Takakiyo Tsujiguchi[1,*], Hideki Obara[2], Shuichi Ono[3], Yoko Saito[1] and Ikuo Kashiwakura[1]

[1]Department of Radiation Sciences, Hirosaki University Graduate School of Health Sciences, 66-1 Hon-cho, Hirosaki, Aomori, 036-8564, Japan
[2]Department of Radiology, Division of Medical Technology, Hirosaki University School of Medicine Hospital, 53 Hon-cho Hirosaki, Aomori, 036-8563, Japan
[3]Department of Radiology and Radiation Oncology, Hirosaki University Graduate School of Medicine, 5 Zaifu-cho Hirosaki, Aomori, 036-8562, Japan
*Corresponding author: Department of Radiation Sciences, Hirosaki University Graduate School of Health Sciences, 66-1 Hon-cho, Hirosaki, Aomori, 036-8564, Japan. Tel: +81-172-39-5964; Fax: +81-172-39-5938; Email: r.tsuji@hirosaki-u.ac.jp
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ABSTRACT

Computed tomography (CT) has recently been utilized in various medical settings, and technological advances have resulted in its widespread use. However, medical radiation exposure associated with CT scans accounts for the largest share of examinations using radiation; thus, it is important to understand the organ dose and effective dose in detail. The CT dose index and dose–length product are used to evaluate the organ dose. However, evaluations using these indicators fail to consider the age and body type of patients. In this study, we evaluated the effective dose based on the CT examination data of 753 patients examined at our hospital using the size-specific dose estimate (SSDE) method, which can calculate the exposure dose with consideration of the physique of a patient. The results showed a large correlation between the SSDE conversion factor and physique, with a larger exposure dose in patients with a small physique when a single scan is considered. Especially for children, the SSDE conversion factor was found to be 2 or more. In addition, the patient exposed to the largest dose in this study was a 10-year-old, who received 40.4 mSv (five series/examination). In the future, for estimating exposure using the SSDE method and in cohort studies, the diagnostic reference level of SSDE should be determined and a low-exposure imaging protocol should be developed to predict the risk of CT exposure and to maintain the quality of diagnosis with better radiation protection of patients.

Keywords: computed tomography; exposure dose; size-specific dose estimate; pediatric

INTRODUCTION

The use of multidetector row computed tomography (CT) is increasing annually with technological advances, and more CT examinations are performed per unit population in Japan than anywhere else in the world [1]. With this rise in the use of CT, the International Commission on Radiological Protection has highlighted the importance of technical education and proper dose control, as we cannot ignore the problem of exposure dose during CT examinations [2].

This issue has prompted interest in understanding the exposure dose and developing technology to reduce exposure. For example, de González *et al.* proposed that 3.2% of all cancers in Japan develop due to exposure to diagnostic radiation [3]. The risk of CT exposure in their study was based on the linear no-threshold hypothesis. This finding is still controversial, but it is known that radiation exposure via medical imaging has a large impact on patients. Although more and more reports are evaluating organ dose from CT examinations [4–6], assessing the organ dose in patients with consideration of their body type remains very difficult. Recently, the volumetric CT dose index ($CTDI_{vol}$) and dose–length product (DLP) have been used to evaluate the exposure dose. However, evaluations using these indicators fail to consider the age and body type of the patients [7, 8]. In general, the $CTDI_{vol}$ is calculated based on the presence of polymethyl methacrylate phantoms, which are available in two diameters: 16 cm and 32 cm [9–11]. Therefore, these indicators are not estimations of the dose *per se*, including the physique and age of each patient. Since it is necessary to resolve the problem to consider organ dose and/or

effective dose estimation, and although there are several reports verifying the relationship between CTDI and body type by phantom study and simulation [12, 13], it is impossible to reproduce and examine similar experiments.

To resolve these issues, the American Association of Physicists in Medicine (AAPM) devised the size-specific dose estimate (SSDE) method, a new index that takes into account the size of the patient for $CTDI_{vol}$ determination [14]. SSDE is defined by multiplication of the object correction factor (SSDE conversion factor) normalized with a phantom diameter of the same diameter as 16/32 cm $CTDI_{vol}$. It is therefore possible to use SSDE to calculate the organ dose with an accurate reflection of the physique of the patient. In Japan, the latest diagnostic reference levels (DRLs) were published in 2015 [15] and do not yet reflect values obtained using SSDE. As such, a number of studies have explored the evaluation of SSDE [7, 8, 16]. In addition, many companies and public organizations have developed software programs for evaluating the organ dose and effective dose from CT examinations since the announcement of SSDE. For example, the National Institute of Radiological Sciences has announced the organ dose and effective dose evaluation software program 'WAZA-ARI' [17, 18], and CT imaging companies have developed software programs such as 'ImpactDose' [19]. These programs are designed to evaluate the effective dose of the patient based on the CT examination parameters (e.g. tube voltage and tube current) and the body type of the patient, and ImpactDose in particular can calculate the organ dose using SSDE.

In this study, we collected the data on more than 700 patients (newborns to elderly) who underwent CT in a single year at our hospital (the study period was over 2 years: April 2013–March 2015). Therefore, by conducting simulation based on data from CT examinations carried out at our hospital, the usefulness of the SSDE conversion factor value indicated in the AAPM report was examined.

MATERIALS AND METHODS

Patient selection and CT instrument

We obtained data and performed our study on 753 patients (children: 163, adults: 590) who underwent CT imaging of the trunk region at Hirosaki University Hospital from April 2013 to March 2015 (Table 1). Among the 163 children, multiple scans were performed in 41 patients and single scans in 122. For adults, we extracted only the data for those who underwent single scans. All scans were performed using a Discovery CT750 HD (GE Healthcare UK Ltd, Little Chalfont, England) and a SOMATOM Definition AS (Siemens, Munich, Germany) at Hirosaki University Hospital. In addition, data collection was carried out after obtaining approval from the ethics committee of Hirosaki University Graduate School of Medicine (no appointment, no approval number).

Table 1. Number of patients

Age (years)	Male	Female	Total
0–1	21	16	**37**
2–5	16	10	**26**
6–10	16	10	**26**
11–15	36	38	**74**
>16	312	278	**590**
Total	**401**	**352**	**753**

Data collection

Information on the age, sex, body size, imaging parameters (tube voltage, $CTDI_{vol}$, DAS, pitch, slice) and imaging range were collected for patients who underwent imaging of the trunk region. The physique was measured that seemed to have the thinnest diameter within the inspection range on the display (Fig. 1). We obtained information on the CT examination findings only and the patient characteristics mentioned above, not the patient name or ID. Our collected information concerned only the data necessary for calculation of the exposure dose.

Exposure dose analyses and calculation of SSDE

Using the collected data, the exposure dose and SSDE were calculated with the ImpactDose (Patient Dose Determination at CT Scanners) software program, version 2.2.2 (CT imaging, Erlangen, Germany) [19]. This program calculates the exposure dose from a CT scan using a Monte Carlo simulation with SSDE. Of note, the SSDE conversion factor was in compliance with the report of the AAPM [14]. This software program assesses six types of phantom: newborn; ages 1, 5, 10, and 15 years; and adult (≥16 years of age). When calculating the exposure dose, we selected the appropriate phantom (the one most similar to the patient), input the anterior–posterior (AP) diameter and lateral (LAT) diameter, and performed SSDE. In this study, we calculated the SSDE and the exposure dose using this software for all cases.

Although it was introduced in the introduction, SSDE is defined by multiplication of the object correction factor (SSDE conversion factor) normalized with a phantom diameter of the same diameter as 16/32 cm $CTDI_{vol}$ again. The SSDE conversion factor also includes the conversion coefficient from air-absorbed dose to tissue-absorbed dose. The $CTDI_{vol}$ cannot reflect the patient's body size in the exposure dose evaluation, and SSDE is an index that considers the patient's body size [15].

Actual measurement of $CTDI_{vol}$

In this study, to calculate the SSDE and exposure dose based on the CT examination data, we needed to consider whether or not the displayed $CTDI_{vol}$ should be used in the simulation. The $CTDI_{vol}$ in the scan protocol of each region was measured using a 9015 dosimeter and 10 × 5-3CT chamber (Radcal Corporation, Monrovia, CA, USA).

With CT imaging, X-rays are emitted with the X-ray tube in rotation. The point of the highest dose in the body axis direction (z-axis direction) is the center of the beam width (isocenter), and the dose decreases with distance from the isocenter. The line integral dose of this profile is expressed as follows (1):

$$\text{Integral dose} = \int_{-\infty\ \text{mm}}^{+\infty\ \text{mm}} D(z) \qquad (1)$$

where $D(z)$ denotes the integrated value of the dose profile in the z-axis direction. Next, the $CTDI_{100}$ was calculated using the line

integral dose and the dosimeter described above. $CTDI_{100}$ is expressed as follows (2):

$$CTDI_{100} = \frac{1}{BW}\int_{-\infty 50\ mm}^{+50\ mm} D(z)\,dz \quad (2)$$

In addition, the $CTDI_w$ was subjected to weighting with the $CTDI_{100}$. The $CTDI_{100}$ of the center of the phantom is defined as $CTDI_{center}$, and the $CTDI_{100}$ of four points (up, down, left and right) of the phantom is defined as $CTDI_{periphery}$. Their weighted average is the $CTDI_w$ and is expressed as follows (3):

$$CTDI_w = \frac{1}{3}CTDI_{center} + \frac{2}{3}CTDI_{periphery} \quad (3)$$

The $CTDI_{vol}$ was then corrected using the pitch factor of a helical scan as follows (4):

$$CTDI_{vol} = \frac{CTDI_w}{\text{pitch factor}} \quad (4)$$

The average $CTDI_{vol}$ was determined using five actual measurements. By comparing the measured values and the console value, we determined whether or not to use the console value in the simulation.

Preparation of figures and statistical analysis

Figures were prepared and statistical analysis was performed using the Origin software package (OriginLab Pro version 8.0, Northampton, MA, USA) and SPSS version 17.0 (IBM, Chicago, IL, USA) for Windows.

RESULTS

Comparison of the measured and displayed $CTDI_{vol}$ values

The $CTDI_{vol}$ is an indicator used for the functional evaluation of the CT device. In addition, it is an important indicator for calculating the SSDE and organ dose. Evaluating the accuracy of the $CTDI_{vol}$ value in the dose report was expected to help determine the accuracy of the simulation in the present study. Therefore, we measured the $CTDI_{vol}$ and compared the result with the displayed value. The results of this measurement are shown in Table 2. Relative errors between the displayed value and measured value were 0.4–2.7%. The guidance level recommends an error range of 20% in Japan, and these results were within this general range of relative errors. Therefore, we confirmed the accuracy of the $CTDI_{vol}$ value on the console used for exposure dose simulation in this study.

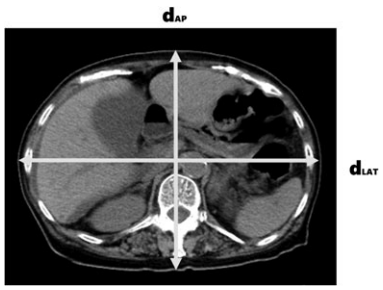

Fig. 1. Diameter calculation. We measured the diameter based on CT images of the console after imaging. The measured points are part of the abdomen, and the LAT is minimized.

Exposure dose simulation value for children using SSDE

The effective doses in each examination using SSDE are shown in Fig. 2. These results are the results for each examination, and it is necessary to be aware that there are differences in the number of scans. Given the possibility of undergoing dynamic CT multiple times in a single year, receiving 40 mSv in a single examination results in a very high exposure to radiation for the patient.

Comparison of $CTDI_{vol}$ and SSDE

SSDE considers the patient's body type based on a calculated factor obtained by measuring the AP and LAT diameter of the patient; the $CTDI_{vol}$ listed in the dose report is then multiplied by this factor to obtain the SSDE. We therefore investigated the difference between the SSDE and $CTDI_{vol}$ (Fig. 3). In Fig. 3, the *x*-axis represents the $CTDI_{vol}$ values from the dose report, and the *y*-axis represents the SSDE. The dotted line represents the direct proportion ($y = x$); patients with small body types have higher SSDE. In our hospital, it is plotted above the dotted line in most patients. In other words, this means that most patients are of the standard type or thin type, suggesting that exposure dose estimation using $CTDI_{vol}$ will be underestimated. This means that the exposure dose to risk organs is expected to be higher than the value calculated using only the $CTDI_{vol}$. The effects of the age and body size on the calculated organ dose and effective dose are shown in Fig. 4. The *y*-axis

Table 2. Parameters of measured $CTDI_{vol}$

Parameter	Discovery CT 750HD	SOMATOM Definition
Peak kilovoltage (kVp)	120	120
Tube current (mA)	150	330
Slice (mm)	5	4.8
DAS	4	6
Beam collimation (mm)	20	28.8
Rotation speed (rot/ms)	2	1
Scan FOV (mm)	16	16
Phantom diameter (cm)	16	16
$CTDI_{vol}$ (measured value) (mGy)	**13.4**	**39.7**
CTDIvol (displayed value) (mGy)	**13.3**	**40.8**
Error rate (%)	**0.4**	**2.7**

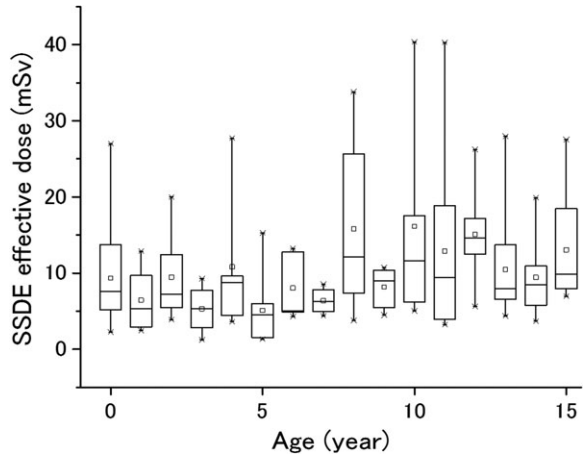

Fig. 2. Exposure dose data using the SSDE in children. Effective dose calculated by simulation is indicated by box plot. The plots above and below the box show the maximum and minimum values. A 10-year-old female, who was exposed to 40.4 mSv (five scans/examination).

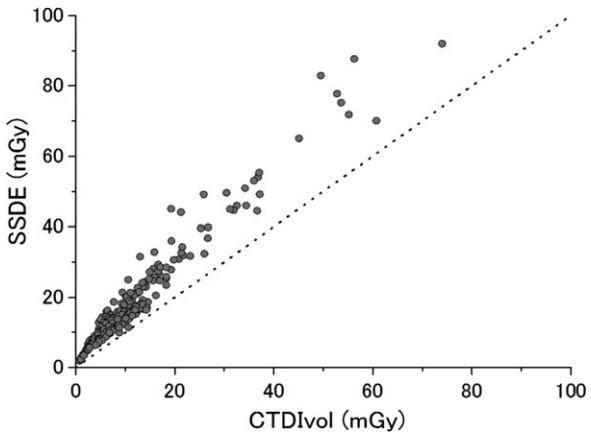

Fig. 3. The relationship of $CTDI_{vol}$ and SSDE in each inspection and each patient. The SSDE was larger than the $CTDI_{vol}$ in all patients at our hospital. The dotted line represents $y = x$.

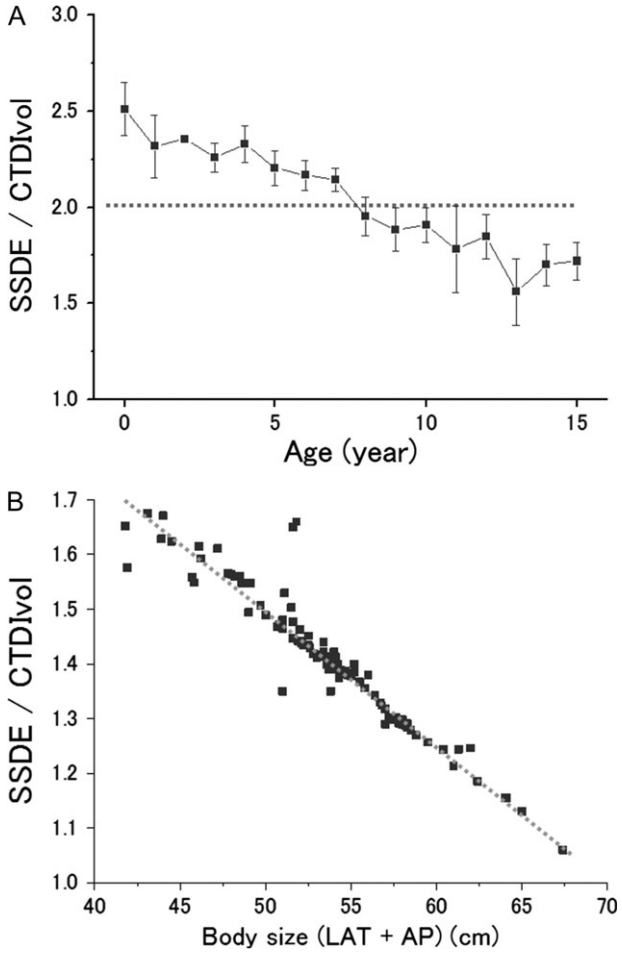

Fig. 4. Exposure dose versus age and physique. The *y*-axis of both graphs shows the $SSDE/CTDI_{vol}$. (A) The $SSDE/CTDI_{vol}$ is higher for younger ages. In particular, at ≥7 years of age, the actual exposure dose may be >2-fold the dose calculated using the $CTDI_{vol}$. (B) The body size and exposure dose are strongly correlated. Furthermore, the exposure dose decreased as the body size increased. $R^2 = 0.961$.

represents the SSDE conversion factor ($SSDE/CTDI_{vol}$) in both graphs, and the *x*-axis represents the age (0–15 years old) in Fig. 4A and body type (LAT + AP) in Fig. 4B. The lower limit of the *y*-axis is 1.0 ($SSDE > CTDI_{vol}$) in both graphs, and we had no extremely obese patients at our hospital. In children 0–7 years of age, the $SSDE/CTDI_{vol}$ was >2.0, suggesting exposure to particularly high doses. Furthermore, Fig. 4B showed a strong correlation between the body type and the exposure dose, suggesting that the exposure dose may be underestimated by evaluations using $CTDI_{vol}$ in patients with a thin body type.

DISCUSSION

In this study, we investigated the effective dose for CT examinations with consideration of patients' body type using SSDE in a large population and considered what kinds of features were associated with the effective dose in each age group and body type. We confirmed that the error between the measured CTDI and the $CTDI_{vol}$ of the dose report was very small in the CT system used in our hospital (Table 2). The simulation software program ImpactDose used in this study calculates the organ absorbed dose using the Monte Carlo method. Since it is experimentally difficult to measure the dose actually absorbed by the human body, it is difficult to determine the accuracy of this calculated absorbed dose. However, as shown in Table 2, the accuracy of the input parameters necessary for the simulation, such as $CTDI_{vol}$, is guaranteed. Using ImpactDose, our group confirmed that

effective dose in pediatric patients exceeded 40 mSv at maximum in our hospital (Fig. 2). In addition, the number of obese patients at our hospital is very small, and the effective dose calculated using SSDE was higher than that determined via the conventional method using $CTDI_{vol}$ alone in all cases (DLP). Given these results, when estimating the organ dose and effective dose for pediatric patients and the standard and thin body type patients, the SSDE-corrected value is less likely to underestimate the exposure dose than the conventional method using $CTDI_{vol}$ and DLP, making SSDE a very effective method [20, 21].

The effective dose of chest/abdomen CT in adults is said to be ~15 mSv per examination [4], but the results of the present study suggest that the actual volume may be 1.5 to 2.0 times higher than the values in previous studies (Fig. 4). However, in the AAPM report, it is stated that there is a wide range of changes in physique, especially in children, even at the same age. In our study, although the SSDE conversion factor exceeds 2.0 under the age of 7 years, it is necessary to extensively analyze SSDE (SSDE conversion factor) of pediatric patient data at each hospital and investigate consistency. Additionally, the cumulative dose per patient was not calculated in this study, as some patients may have undergone several examinations in a short period of time or multiple scans in a single examination (such as with dynamic CT), so we must carefully consider the biological effects of effective dose with CT examinations.

For CT, which does use ionizing radiation, it is essential to establish criteria carefully, especially in Japan where a large number of CT examinations are conducted. Various strategies have been considered in an effort to reduce CT exposure, such as developing an imaging protocol that takes into consideration the patient's age and body type, performing ultrasonic examinations with a reduced number of CT scans, and considering the omission of either simple/contrast-enhanced CT. SSDE is likely to not only improve risk prediction of CT exposure but also to encourage the establishment of DRLs based on SSDE and development of imaging protocols with lower exposure, while maintaining the quality of the diagnosis. Techniques for reducing the exposure on CT include image reconstruction using CT automatic exposure control [22–24], lower tube voltage CT [25–28], and a successive approximation method [29]. By incorporating SSDE into these techniques, low-exposure diagnostic methods tailored to individual patients may become possible.

CONFLICT OF INTEREST

The authors have no relevant conflicts of interest to disclose.

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