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Relationship between radiation dose indices and patient size in adult brain computed tomography

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Abstract – The relationship between radiation dose indices and patient size was investigated in adult brain CT scans to assess the significance of considering the patient size for radiation dose management. Two hundred patients who underwent brain CT using automatic exposure control were enrolled. The radiation dose indices (volume CT dose index, CTDIvol; size-specific dose estimate, SSDE; dose length product, DLP) were compared with the head size indices (effective diameter, ED; water-equivalent diameter, WED) and body weight. The CTDIvol and SSDE correlated positively with the ED and WED. The correlations were higher for the WED than the ED and for the CTDIvol than the SSDE. Although the DLP also correlated positively with the ED and the WED, the correlations were lower than those for the CTDIvol and the SSDE. The CTDIvol and SSDE showed significant positive correlations with body weight, but the correlations were lower than those for the ED. In conclusion, the radiation dose indices in adult brain CT correlate with the head size indices. Consideration of the head size indices is recommended for radiation dose management in brain CT. The relationship between the radiation dose indices and body weight may be of some significance when the head size indices are not readily available.

Keywords: Radiation dose / computed tomography / brain / automatic exposure control

1 Introduction

Epidemiologic studies have demonstrated an increased incidence of brain tumours in children who underwent computed tomography (CT) of the brain (Pearce *et al.*, 2012; Mathews *et al.*, 2013; Meulepas *et al.*, 2019). When using CT, the radiation dose to the patients should be reduced while maintaining clinical benefits for the patients. The volume CT dose index (CTDIvol) and dose length product (DLP) commonly serve as indices of CT radiation dose (ICRP, 2007, 2017). For brain CT, the CTDIvol is calculated from the imaging parameters and the absorbed dose measured using a 16-cm dosimetry phantom. The DLP is an integral of the CTDIvol over the longitudinal scan range and reflects total radiation exposure in an imaging series.

Even when CTDIvol values are identical in brain CT, the actual absorbed dose to the patient varies depending on the size of the patient's head. As the head size increases, X-rays become more severely attenuated in sections that are imaged and the proportion of X-rays that reach tissues distant from the incident side decreases, resulting in a reduced absorbed dose. The size-specific dose estimate (SSDE) is a dose index that considers differences in attenuation between the patient and the dosimetry phantom (AAPM, 2011, 2019). The effective diameter (ED) and water equivalent diameter (WED) are often used as indices of the cross-sectional size. The ED is defined as the geometric mean of the anteroposterior and lateral diameters. Even at an identical ED, attenuation is stronger in sections containing more bony tissues. The WED is calculated considering differences in attenuation strengths among tissues. The SSDE for brain CT can be calculated from the CTDIvol and WED (AAPM, 2019).

In a larger patient, X-ray attenuation in the imaging section is stronger; therefore, more radiation exposure is required to preserve image quality. Automatic exposure control (AEC) evaluates the strength of attenuation of the imaging subject mainly based on the scout image and automatically modulates the tube current and thus the radiation dose (Kalra *et al.*, 2004; Lee *et al.*, 2008; Inoue, 2022a). AEC is an essential tool to optimize the radiation dose in CT.

In brain CT, it is appropriate that the dose index increases with increasing head size, from the aspect of optimization. In children, the head size shows a rapid initial increase during the early stage of birth, followed by a slow increase (Kleinman

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et al., 2010; Kawamoto et al., 2020; Sekkat et al., 2024). For radiation dose management in paediatric brain CT, age grouping has been recommended to assess the appropriateness of radiation dose (ICRP, 2017, European Commission, 2018). It has been demonstrated that the CTDIvol (Inoue et al., 2022b) and SSDE (Fujii et al., 2023) increase with age and weight in paediatric brain CT performed with AEC and that the dose indices correlate slightly better with weight than age. Furthermore, the CTDIvol (Inoue et al., 2022c) and SSDE (Fujii et al., 2023) have been shown to be highly correlated with the WED in paediatric brain CT, suggesting that AEC achieves appropriate dose modulation according to the head size. Although the WED is not necessarily readily available, body weight is a convenient indicator of the patient size and is suitable for routine radiation dose management. In adults, the radiation dose indices in CT of the body have been reported to correlate with body weight (Israel et al., 2010; Iball and Tout, 2014; Inoue et al., 2016, 2022d) and the WED (Fujii et al., 2017; Boere et al., 2018; Klosterkemper et al., 2019), and body weight is considered in radiation dose management.

Adult head sizes do not differ greatly among patients, and the patient size is not usually considered in radiation dose management for adult brain CT. Even in a report that determined the diagnostic reference level for groups divided according to the ED, the patient size was not considered for brain CT (Moghadam et al., 2021). However, four of eight facilities included in the study used AEC, which indicates that the head size was considered in clinical practice. In this study, we investigated the relationship between the patient size (head size or body size) and radiation dose indices in adult brain CT performed using AEC to assess the significance of considering the patient size for radiation dose management.

2 Materials and methods

2.1 Subjects

Patients who underwent brain CT for clinical indications according to our standard protocol were retrospectively analysed. A 64-detector-row CT scanner (Optima CT 660 Discovery Edition; GE Healthcare, Milwaukee, WI, USA) was used. Two hundred adult patients (100 females and 100 males), aged 20 years or older, were consecutively enrolled. The exclusion criteria were no body weight record, weight larger than 100 kg, and mean WED longer than 20 cm. The upper limits of weight and WED were set to exclude outliers in terms of body size or head size. When CT scans were repeated in one patient, data of the first scan for the patient were used for analysis. Patient age, height, weight and body mass index (BMI) (means ± SDs) were 65.4 ± 16.5 years, 159.3 ± 9.7 cm, 56.4 ± 13.2 kg and 22.1 ± 4.1 kg/m^2, respectively. This study was approved by the Kitasato University Medical Ethics Organization (B22-166), and need for informed consent was waived due to its retrospective design.

2.2 Imaging procedures

The head of the patient was placed on the head holder, and the posteroanterior and lateral scout images were obtained in that order. Axial CT images parallel to the orbitomeatal line were acquired covering the lower margin of the posterior fossa and the top of the brain. Inbuilt AEC software (Auto mA and Smart mA) was used to modulate the tube current, with a noise index of 3.3, a maximum current of 350 mA and the minimum current of 50 mA. The software adjusts the tube current so that the noise in the CT image reconstructed by filtered back-projection equals the noise index. Lateral scout images were used to estimate the attenuation strength and modulate the tube current. Additionally, organ dose modulation was applied over the orbit to reduce radiation dose to the eye lens. This function selectively reduces radiation exposure from the anterior direction and does not change posterior exposure (Gandhi et al., 2015; Dixon et al., 2016). Other imaging parameters were axial mode, a tube voltage of 120 kV, a rotation time of 1 s, a beam width of 20 mm, a slice thickness of 5 mm and a slice increment of 5 mm. Adaptive statistical iterative reconstruction (ASiR, 50% IR blending) was used for image reconstruction.

2.3 Data analysis

The CTDIvol and DLP automatically calculated by the CT scanner were recorded. The ED and WED were determined based on CT images using the dose management system Radimetrics (version 3.4, Bayer Medical Care Inc., Indianola, PA, USA), and the values averaged over the entire imaging range were used for analysis. The ED calculated by Radimetrics is not the geometric mean of the anteroposterior and lateral diameters but the diameter of a circle with the same area as the image cross-section. The f factor was calculated as $f = 1.9852\,\exp(-0.0486\,\text{WED})$, and the SSDE was obtained by multiplying the f factor by the CTDIvol (AAPM 2019). The dose indices (CTDIvol, SSDE and DLP) were plotted against the head size indices (ED and WED), followed by linear regression. The relationships of the CTDIvol and SSDE with body size indices (body weight, body height and BMI) were also assessed.

2.4 Statistical analysis

Correlations were examined using linear regression. The significance of the correlation was examined using a test of no correlation. The Hittner, May and Silver's modification of Dunn and Clark's z with common items was used to compare correlation coefficients. A parallel slopes test was performed using analysis of covariance (ANCOVA) to compare the slopes of the regression lines. In ANCOVA, parallel slopes were tested by adding an interaction term to the model for the factor by the covariate. Analysis was performed using R software (version 4.0.3, R Foundation for Statistical Computing, Vienna, Austria).

3 Results

The WED, ED, CTDIvol, SSDE and DLP were 16.6 ± 0.7 cm, 15.3 ± 0.6 cm, 38.6 ± 3.8 mGy, 34.1 ± 2.3 mGy and 582 ± 74 mGy · cm, respectively. The CTDIvol and DLP were lower than the Japanese diagnostic reference levels (CTDIvol, 77 mGy; DLP, 1350 mGy · cm) (Kanda et al., 2021).

The CTDIvol showed high positive linear correlations with the ED and WED (Fig. 1, $p < 0.001$ for both). The correlation between the CTDIvol and WED was higher than that between the CTDIvol and ED ($p < 0.001$).

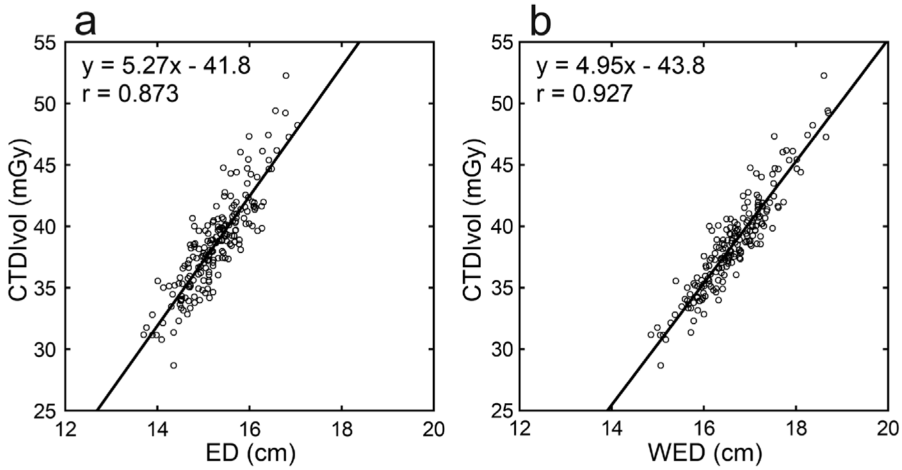

Fig. 1. Relationships of CTDIvol against ED (a) and WED (b). The solid lines represent regression lines.

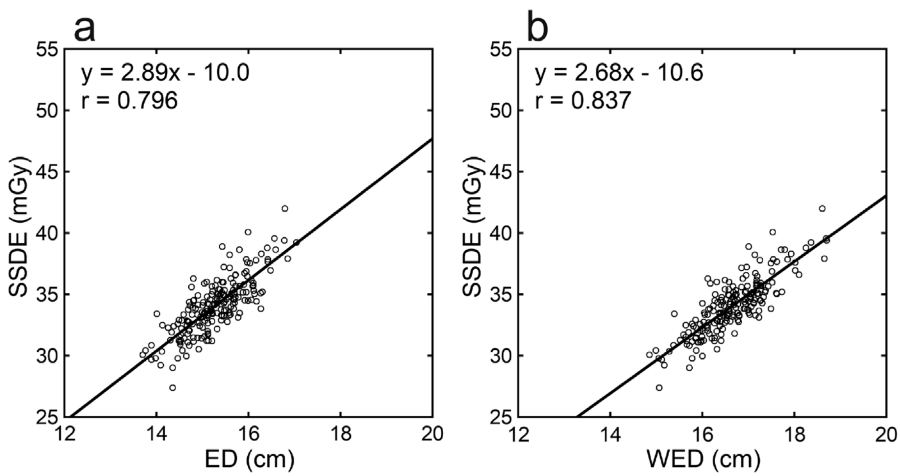

Fig. 2. Relationships of SSDE against ED (a) and WED (b). The solid lines represent regression lines.

The SSDE also showed positive linear correlations with the ED and WED (Fig. 2, $p < 0.001$ for both). The correlation between the SSDE and WED was higher than that between the SSDE and ED ($p = 0.006$). When correlations with the ED and WED were compared between the CTDIvol and SSDE, the correlation coefficients were lower ($p < 0.001$ for both), and the slopes of the regression lines were smaller ($p < 0.001$ for both) for the SSDE.

Although the DLP showed positive correlations with the ED and WED (Fig. 3, $p < 0.001$ for both), the correlation was lower for the DLP than for the CTDIvol and SSDE ($p < 0.001$ for all). The plots of the DLP against the WED appeared to be divided into two groups: high-DLP and low-DLP groups. The DLP at a given WED was higher in the high-DLP group than in the low-DLP group.

The CTDIvol and SSDE showed significant positive correlations with body weight (Fig. 4, $p < 0.001$ for both), body height (Fig. 5, $p < 0.001$ for both) and BMI (Fig. 6, $p < 0.001$ for both). Although the correlation coefficients were highest for weight among the body size indices, they were definitely lower for weight than for the ED ($p < 0.001$ for both).

4 Discussion

The CTDIvol showed high positive linear correlations with the ED and WED, indicating that the AEC used in this study modulated the radiation dose in a manner that closely reflected X-ray attenuation by the head. Whereas the ED is a simple index of cross-sectional size, the WED is calculated considering differences in attenuation among tissues. The correlation with the CTDIvol was higher for the WED than the ED, further suggesting successful dose modulation by AEC according to the attenuation strength. For radiation dose management, evaluating the relationship between the CTDIvol and the ED or WED appears to be helpful. From this relationship, a typical dose at the facility for any ED or WED can be determined. During daily dose management, it is recommended to plot the CTDIvol against the ED or WED and identify outliers to be investigated.

The CTDIvol represents CT scanner output rather than the absorbed dose to the patient. When the head is larger than the 16-cm dosimetry phantom, the absorbed dose to the patient is lower than in the CTDIvol because of increased attenuation in

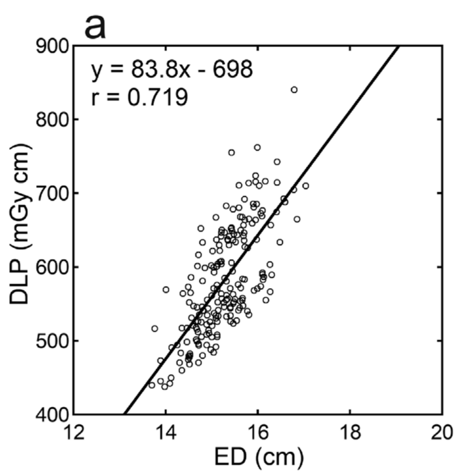

Fig. 3. Relationships of DLP against ED (a) and WED (b). The solid lines represent regression lines.

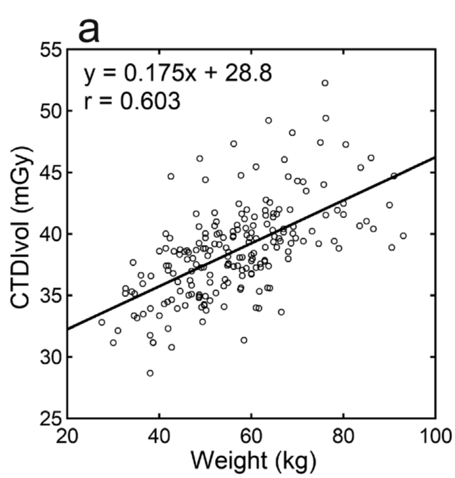

Fig. 4. Relationships of CTDIvol (a) and SSDE (b) against body weight. The solid lines represent regression lines.

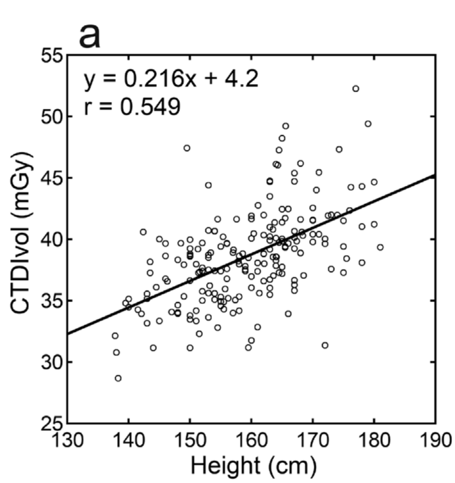

Fig. 5. Relationships of CTDIvol (a) and SSDE (b) against body height. The solid lines represent regression lines.

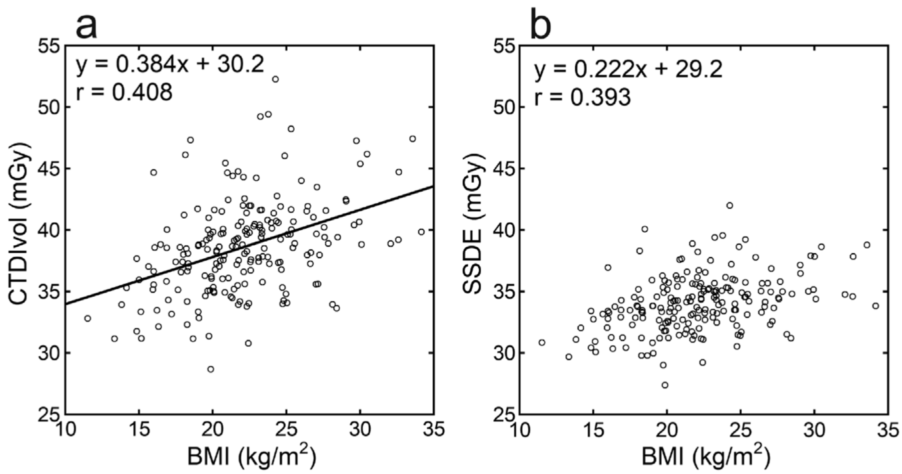

Fig. 6. Relationships of CTDIvol (a) and SSDE (b) against BMI. The solid lines represent regression lines.

imaging sections. The SSDE is an index of the patient dose that considers tissue attenuation, and is calculated by multiplying the CTDIvol by the f factor determined based on the WED. As the head size increases, the f factor decreases; therefore, the SSDE increases less than the CTDIvol. However, it was demonstrated that the SSDE still increased with increasing ED or WED, suggesting that a larger head receives higher absorbed dose in brain CT. Therefore, it is desirable to consider the head size in radiation dose management using the SSDE.

The DLP is the integral of the CTDIvol over the longitudinal scan range. The plots of the DLP against the ED and WED appeared to be divided into two groups, and the overall correlation of DLP with ED or WED was relatively low. In routine radiation dose management, CT scans with exceptionally high or low radiation doses are identified, and the cause of each outlier is investigated. There are larger variations in DLP at a given head size than in CTDIvol, and the sensitivity for identifying outliers caused by technical problems other than inappropriate setting of the scan range would be lower for the DLP. Assessment of the CTDIvol appears to be indispensible in identifying outliers in brain CT, and that of the DLP would be supplementary. In this study, we performed CT in the axial mode but not helical mode, with a beam width of 2 cm. As a result, the scan length varied not continuously but in 2-cm increments, which is responsible for the division of the plots into two groups. The use of the helical mode may improve the correlation of the DLP with the ED or WED.

A high correlation between radiation dose indices and body weight has been reported for CT of the body (Israel *et al.*, 2010; Iball and Tout, 2014; Inoue *et al.*, 2016, 2022d). In this study, the CTDIvol and SSDE in brain CT showed positive correlations with body size indices, including body weight, body height and BMI. Although the correlations were highest for weight among them, they were relatively low, presumably reflecting the weak relationship between the head size and body weight. Considering the body size appears to be less significant in brain CT than body CT. The ED and WED are preferred to body weight to identify examinations that delivered exceptionally high radiation doses. However, the WED and ED are not always readily available. When they are unavailable, considering body weight may be of some significance for radiation dose management.

There are limitations to this study. Only one CT scanner was used, and radiation dose was modulated using inbuilt AEC software. The type of AEC software and parameter settings of the software affect dose modulation (Inoue, 2022a); therefore, they would influence the relationship between the head size and dose index. Studies using different methods of dose modulation remain to be done. Moreover, optimization of radiological imaging involves reducing radiation dose while maintaining diagnostic performance. In this study, we showed that radiation dose indices reflect the WED when using AEC; however, we did not evaluate image quality and did not show whether optimization was actually achieved.

5 Conclusion

When adult brain CT was performed using AEC, the CTDIvol showed high positive correlations with the ED and WED, suggesting that AEC achieved dose modulation reflecting X-ray attenuation in the head. It is recommended to evaluate the relationship of the CTDIvol with the ED or WED for radiation dose management of adult brain CT. As the ED and WED increased, the SSDE and DLP also increased. However, the correlation with the ED and WED was relatively weak for the DLP, presumably attributable to imaging in the axial modes. The CTDIvol and SSDE showed weak positive correlations with body weight, and considering body weight may have some significance in dose management for brain CT.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The data are available upon reasonable request from the corresponding author.

Author contribution statement

K. Mitui: Analysis, Interpretation, Writing original draft, Y. Inoue: Conceptualization, Methodology, Interpretation, Writing-Reviewing and Editing, H. Itoh: Data collection, Writing-Reviewing and Editing, H. Hata: Data collection, Writing-Reviewing and Editing, H. Miyatake: Data collection, Writing-Reviewing and Editing, T. Yamane: Data collection, Writing-Reviewing and Editing.

Ethics approval

This study received ethical approval from the Kitasato University Medical Ethics Organization under the protocol number B22-166.

Informed consent

The Kitasato University Medical Ethics Organization waived the need for informed consent.

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