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Validation of SSDE calculation in a modern CT scanner and correlation with effective dose

Nicola Zancopè[1], Francesca De Monte[2]✉, Erica Simeone[1], Angelo Giannone[1], Riccardo Lombardi[1], Alessandro Mele[2], Alessandra Zorz[2], Alessandro Di Paola[3], Francesco Causin[3] & Marta Paiusco[2]

This study aims to validate the Size Specific Dose Estimate (SSDE) provided by a modern Computed Tomography (CT) scanner and investigate its correlation with effective dose (E). SSDE is a size-specific dosimetric index addressing the limitations of the Computed Tomography Dose Index ($CTDI_{vol}$). A set of 60 CT scans of anthropomorphic phantoms, including pediatric and obese models, were acquired and analyzed. SSDE values from the CT scanner were compared with those obtained through an independent Python-based calculation and Radimetrics, a dose monitor software. While the independent calculation and the one with Radimetrics were consistently in agreement, a systematic underestimation by the scanner up to 10% was seen, particularly in chest and abdominal exams. The underestimation, however, remained within the acceptable limits set by AAPM guidelines. Furthermore, a correlation between SSDE and effective dose was identified, suggesting SSDE's potential for more accurate, size-specific radiation dose and risk assessments. These findings highlight the importance of SSDE in enhancing patient-specific dose management, though further validation using patient data is needed to confirm its clinical applicability.

Keywords SSDE, CT, Effective dose, Radiation dose management

The rising demand for Computed Tomography (CT) scans has raised corners regarding the risk of cancer induction in the population from X-ray exposure[1,2]. Thus, it has become essential to optimize acquisition protocols, reducing patient's dose while preserving image quality[3].

Computed Tomography Dose Index ($CTDI_{vol}$) is the standard dosimetric index for CT examinations and it can be used for optimization purposes[4,5]. However, it does not represent a patient dose estimate, but rather a measurement of the machine's output, allowing for the comparison between different CT scanners[6,7]. Being $CTDI_{vol}$ obtained with reference to standardized phantoms, it lacks patient-specific data.

In the AAPM Task Group 204 report[8], the Size Specific Dose Estimate (SSDE) is introduced for body CT exams. This metric is calculated by multiplying the $CTDI_{vol}$ with a correction factor that accounts for the patient's size. The multiplication factor is determined by estimating the patient's effective diameter (D_{eff}) from the anteroposterior and lateral dimensions of the patient. However, tissue attenuation differences within the scanned region of the body are not accounted for by D_{eff}. The AAPM Report 220[9] addresses this issue by introducing the Water Equivalent Diameter (D_w), which evaluates differences in X-ray absorption and allows for a more precise estimate than the effective diameter. The AAPM Report 293[10] further extends the SSDE estimation to head CT procedures, providing the necessary parameters for the $CTDI_{vol}$ to SSDE conversion.

SSDE estimates the average dose to the center of the scanned region[8]; however, organ dose estimation from SSDE has been investigated in various studies, demonstrating its relevance for improving radiation dose management and clinical practice optimization[1,2,11].

As SSDE is gaining importance and recognition, CT vendors are starting to include this metric in the dose report for each exam[12]. A newly installed Philips Incisive CT scanner in the Neuroradiology Unit of the University Hospital of Padua displays both D_w and the SSDE for each scan.

The present work aims to validate the estimation of these parameters provided by the Philips scanner. Eventually, a correlation of the SSDE with the effective dose (E) is sought, deriving useful conversion parameters to assess E in a size-specific fashion.

[1]Department of Physics and Astronomy "Galileo Galilei", University of Padova, Padua, Italy. [2]Medical Physics Department, Veneto Institute of Oncology IOV - IRCCS, Via Gattamelata n. 64, Padua 35128, Italy. [3]Neuroradiology - Pediatric Radiology Unit, University-Hospital of Padua, Padua, Italy. ✉email: francesca.demonte@iov.veneto.it

Materials and methods

Data collection

Sixty CT scans of ATOM CIRS anthropomorphic phantoms (1-year-old, 5-year-old, and adult) were acquired using clinical protocols on the Philips Incisive CT scanner. Head, chest and abdominal scans were acquired on each phantom in order to validate SSDE calculation across different anatomical sites. Supplementary abdominal scans were performed on adult phantoms using dedicated fat layers to simulate obesity. For completeness, all the available tube voltages were used (70, 80, 100, 120, 140 kV). Acquisitions were performed keeping the Automatic Exposure Control (AEC) active.

SSDE and D_w were manually extracted from the dose sheet relative to each CT acquisition, while dosimetric indices such as $CTDI_{vol}$ and DLP were obtained employing a dose-monitoring software (Radimetrics version 3.4.2, Bayer HealthCare, Whippany, NY)[13]. Radimetrics was also used for a second estimation of the D_w and SSDE values, as it calculates them independently of the CT scanner, but only for body and not for head examinations. Moreover, an estimate of the effective dose for each acquisition was extracted from Radimetrics, which uses Monte Carlo simulations on anthropomorphic phantoms and organ weighting factors published in the ICRP 103 report[14,15].

SSDE calculation

To validate the SSDE calculation by the CT scanner, Radimetrics cannot be used, as it lacks the necessary information for head exams. Therefore, a Python (version 3.12.2, Python Software Foundation, Wilmington, DE) script was developed to independently calculate SSDE for each body region according to AAPM guidelines[9,10]. The software identifies the external contour of the phantom for each CT slice using an air-tissue threshold. Among the resulting regions, the largest connected area is selected as the region of interest (ROI) to exclude other contours that are not part of the phantom, such as the table. Then, any holes within this area created during the thresholding process are filled, allowing the ROI to include air-equivalent tissues inside the body, such as the lungs. Following AAPM Task Group 220, D_w is obtained using the Eq. 9:

$$D_w = \sqrt{[\frac{1}{1000} \cdot \bar{CT} + 1] \cdot \frac{A_{ROI}}{\pi}}$$

Where A_{ROI} is the area of the external ROI, and $\bar{CT}$ is the mean CT number in Hounsfield Units (HU) inside the region. SSDE is *then* calculated as[9]:

$$SSDE = [\alpha \cdot e^{-D_w \cdot \beta}] \cdot CTDI_{vol}$$

where α and β are parameters provided in the report for abdomen, thorax and pelvic CT examinations. SSDE of the whole acquisition is then calculated as the average across the slices. For head scans, instead, only the central slice is used, with dedicated α and β values[10]. A scheme of the SSDE calculation process is presented in Fig. 1.

Results and discussion

SSDE verification

To confirm the accuracy of the Python-based SSDE calculation, results were compared with Radimetrics for abdominal and chest exams, as shown in the Bland-Altman plot (Fig. 2, upper-left). Percentage differences between SSDE values are below 3% in absolute value, with a mean of 0.6%, suggesting the equivalence of the two calculation methods. The limits of agreement range from −3.07% to +1.95%, indicating a narrow spread and good agreement between methods.

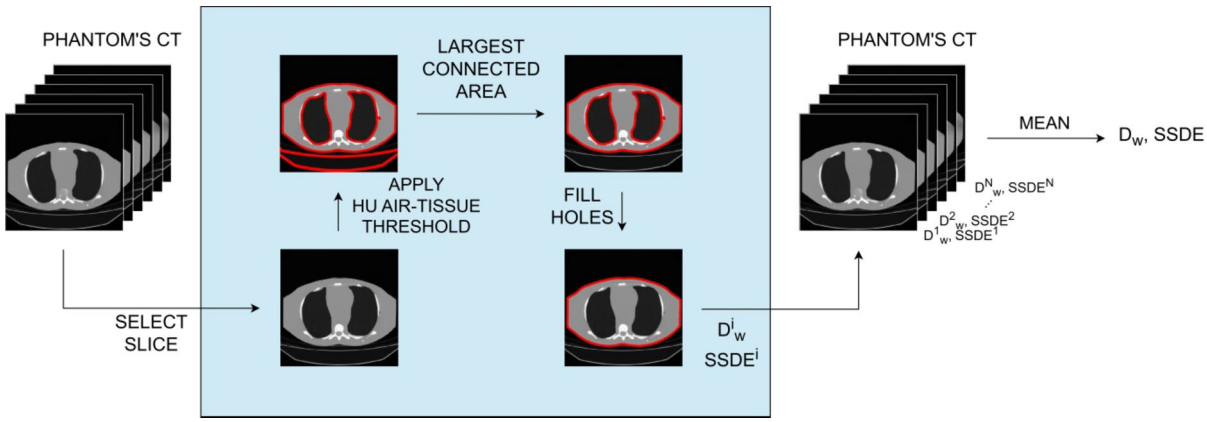

Fig. 1. Flowchart of the SSDE calculation process with the Python script for chest and abdomen examinations. In case of head scans, only the central slice is used in the calculation process.

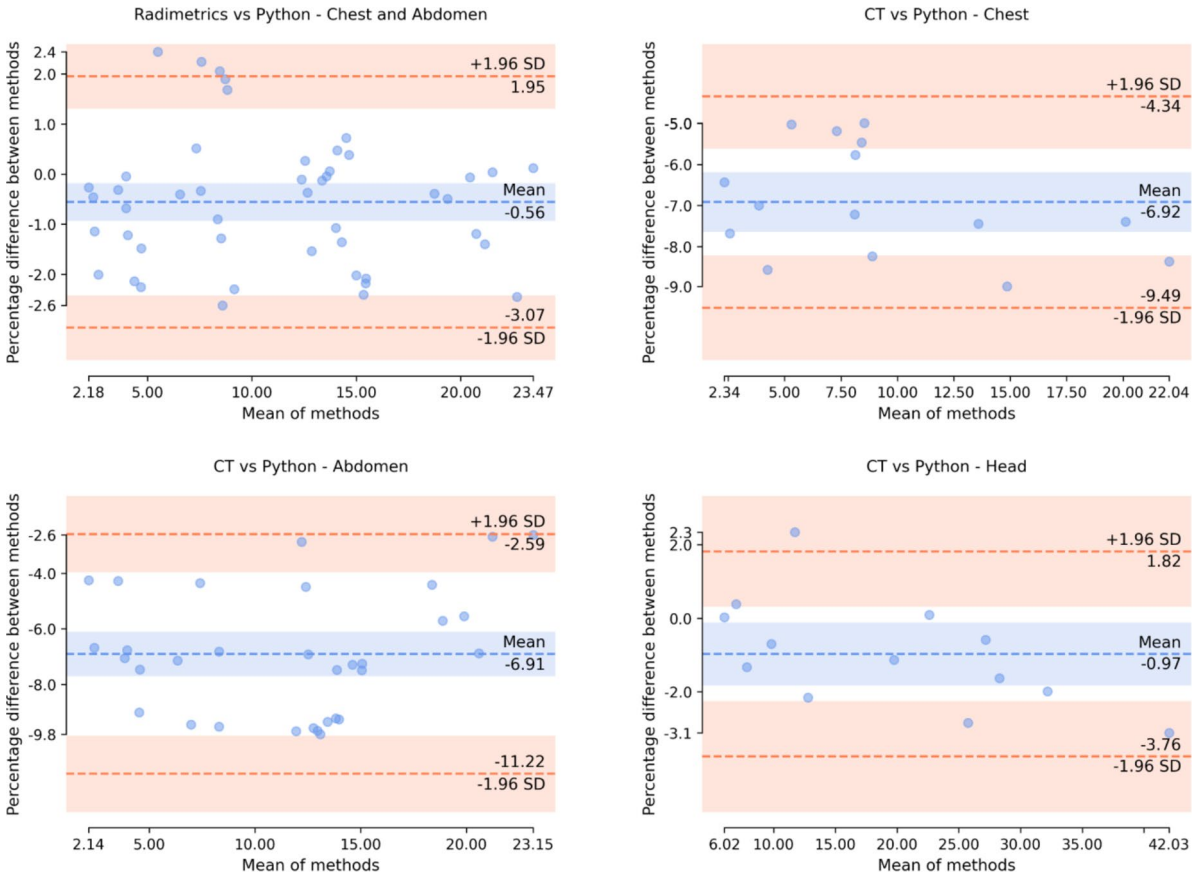

Fig. 2. Bland-Altman analysis of SSDE obtained from Python, Radimetrics and Philips Incisive CT scanner. Data are divided according to anatomical districts as indicated in subplots' titles.

Having validated the Python-based computation, it is possible to consider it the reference and to proceed with a comparison of the values provided by the scanner against the newly established benchmark. The rest of Fig. 2 depicts the Bland-Altman analysis comparing SSDE values from the scanner and Python. The CT scanner underestimates the SSDE by up to 10% for chest and abdomen scans. The limits of agreement range from − 9.49% to -4.34% for chest exams, and from − 11.22% to -2.59% for abdominal ones.

The difference in thorax examination can be explained by the calculation process of the CT scanner, which is performed directly onto the scout image as indicated in the reference technical guide. In fact, AAPM report 220 states that D_w is generally overestimated when calculated over the radiograph in thorax exams, leading to a systematic SSDE underestimation[9]. For abdominal exams, however, the two calculation methods should be equivalent, so the cause of the discrepancy must be found elsewhere. Some possible sources of error are listed in AAPM report 220, such as the calibration of pixel values in water-equivalent attenuation, accounting for table attenuation and patient positioning. Nonetheless, the report states that the D_w from CT localizer can be used, as long as the error remains within 20% of the reference value. In the performed exams on phantoms, the maximum error on the water equivalent diameter is below 11%, meaning that the calculation process for abdominal and chest exams is validated.

For the head scans, the calculation process according to TG 293 guidelines[10] leads to a more consistent estimation between the scanner and the Python script. This is likely because the scanner does not alter the calculation method, while the AAPM protocol requires the calculation only at the central slice of the scan. Also in this case, the calculation of the CT scanner can be considered valid, being the maximum error on the water equivalent diameter below 4%. The mean difference is close to zero and the limits of agreement ranging from − 3.76% to + 1.82% are clinically acceptable.

When considering the use of SSDE values calculated by the CT scanner, even though they are consistent with AAPM guidelines, clinicians need to be aware of the limitations shown above. In a clinical scenario, additional sources of uncertainty may increase the error in SSDE estimation. The reference technical manual of the CT scanner, for example, mentions factors such as the acquisition of CT images beyond the scanogram range, patient anatomy outside the acquisition FOV, and the presence of foreign objects within the scan region. Future studies on patient data will allow for a more detailed investigation of these potential sources of uncertainty.

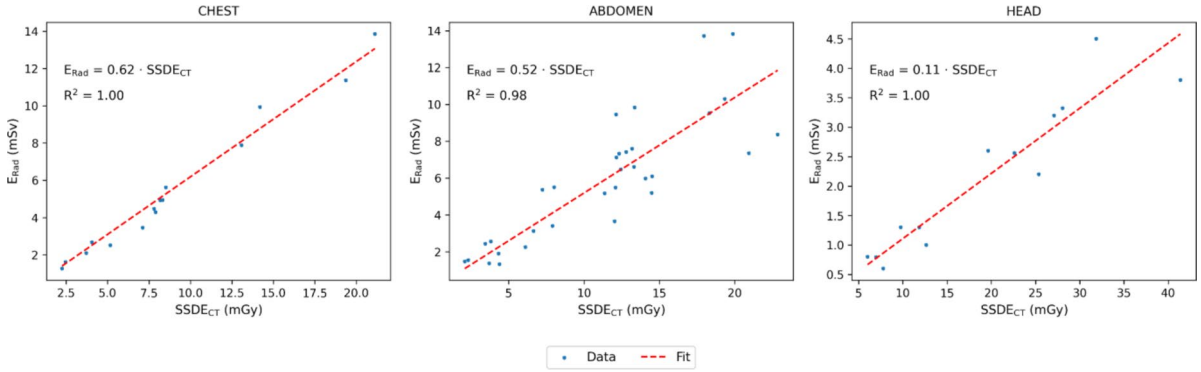

Fig. 3. Effective dose calculated by Radimetrics plotted against the SSDE provided by the Philips Incisive CT scanner. Red lines represent linear fit in the form y = k*x. Data are divided according to anatomical districts.

SSDE and effective dose correlation

Effective dose may be considered as an approximate indicator of possible risk of cancer incidence associated with medical procedures, even though it cannot substitute a detailed assessment of risk for individuals or specific population groups[16,17]. Effective dose in CT examinations can be readily calculated with the DLP using conversion factors depending on age and body region[18,19]. However, the coefficients are obtained from standardized phantoms and may not accurately account for varying patient body sizes[20,21]. The SSDE might address this, as it naturally accounts for the patient's size and attenuation. Nevertheless, the standard DLP-E conversion factor cannot be used to retrieve the effective dose from the SSDE, as stated in the AAPM reports[8,10]. Figure 3 shows the effective dose from Radimetrics (E_{RAD}) plotted against the SSDE from the scanner ($SSDE_{CT}$). A correlation can be seen between the two quantities, despite the limited amount of data points. A linear fit was performed for each region, obtaining conversion coefficients to estimate effective dose from SSDE. Similar findings were reported in literature, where consistent linear relationship between SSDE and the effective dose was observed across different body regions[22]. Overall, the promising results suggest that the relationship between SSDE and E could potentially apply in a clinical scenario, enabling effective dose estimation and cancer risk assessment in a size-specific fashion. However, further studies on patient data will be needed to confirm this possibility.

Conclusions

In the present study, the calculation of SSDE by a modern CT scanner was validated against an independent benchmark. The machine systematically underestimates the size-specific dosimetric index with percentage differences below 10% that, according to AAPM guidelines, validates the computation process. Moreover, a correlation between SSDE and the effective dose was observed, suggesting the potential benefit for a more accurate and size-dependent cancer risk estimation for the patient, provided this relationship holds in a clinical setting.

Data availability

Data can be found in online repository in Zenodo at the URL https://doi.org/10.5281/zenodo.14697157.

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Author contributions

All authors contributed to the study's conception and design. Material preparation and data collection were performed by N.Z., E.S., F.D. and M.P. Data analysis was performed by N.Z., supervised by F.D. and M.P. The first draft of the manuscript was written by N.Z. and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to F.M.

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