A Segmentation-based Automated Calculation of Patient Size and Size-specific Dose Estimates in Pediatric Computed Tomography Scans

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Abstract

Background and Purpose: Size-specific dose estimates (SSDE) have been introduced into computed tomography (CT) dosimetry to tailor patients' unique sizes to facilitate accurate CT radiation dose quantification and optimization. The purpose of this study was to develop and validate an automated algorithm for the determination of patient size (effective diameter) and SSDE. **Materials and Methods:** A MATLAB platform was used to develop software of algorithms based on image segmentation techniques to automate the calculation of patient size and SSDE. The algorithm was used to automatically estimate the individual size and SSDE of four CT dose index phantoms and 80 CT images of pediatric patients comprising head, thorax, and abdomen scans. For validation, the American Association of Physicists in Medicine (AAPM) manual methods were used to determine the patient's size and SSDE for the same subjects. The accuracy of the proposed algorithm in size and SSDE calculation was evaluated for agreement with the AAPM's estimations (manual) using Bland–Altman's agreement and Pearson's correlation coefficient. The normalized error, system bias, and limits of agreement (LOA) between methods were derived. **Results:** The results demonstrated good agreement and accuracy between the automated and AAPM's patient size estimations with an error rate of 1.9% and 0.27% on the patient and phantoms study, respectively. A 1% percentage difference was found between the automated and manual (AAPM) SSDE estimates. A strong degree of correlation was seen with a narrow LOA between methods for clinical study ($r > 0.9771$) and phantom study ($r > 0.9999$). **Conclusion:** The proposed automated algorithm provides an accurate estimation of patient size and SSDE with negligible error after validation.

Keywords: Algorithm, automation, body size, computed tomography scan, image segmentation, pediatric, radiation dosage, size-specific dose estimate

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Introduction

The computed tomography (CT) scan is a vital diagnostic tool in medicine because of its excellent spatial resolution and high image contrast. However, in the last few years, worries about radiation exposure from CT scans have grown.[1] It is reported that CT scans may account for up to 75% of the total radiation dose received from medical devices and up to 5%–11% of this is performed on pediatrics.[2,3] Besides, a child's longer lifespan and greater radiosensitivity make them more vulnerable to long-term radiation impacts, which raises concerns about increasing danger from radiation exposure to this demography.[4] Over the years, volume CT dose index ($CTDI_{vol}$) and dose length product (DLP) have been the standard dose indices used to indicate radiation dosage from CT examinations. However, the constraint of $CTDI_{vol}$ and DLP is that they are just a projected dose rather than the actual absorbed dose by the patient, based only on scanner output for

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a specific standard normalized condition.[5,6] Theoretically, a patient's radiation dosage relies on a few associated factors, such as patient size, tissue attenuation properties, and scanner output. Besides, it has been shown that $CTDI_{vol}$ can be used as a standardization factor for organ dose determination for specific patient sizes and that the relationship to patient size was predictable across scanner models.[7-9] The findings pave the way for a new promising way to deal with radiation dosage from CT scans, allowing the assessment of size-specific dose, scanner-specific, and organ-specific doses using the patient size and scanner-reported $CTDI_{vol}$.[9-12] Thus, getting precise data about patient size became pivotal in assessing the patient dose received from a CT scan.

Consequently, the size-specific dose estimate (SSDE) method was introduced in 2011 by the American Association of Physicists in Medicine (AAPM), it detailed the physical (calipers) and techniques of determining patient size from axial and topograph CT images.[13] To calculate SSDE from $CTDI_{vol}$, two approaches were suggested: using the patient's single geometric dimension or combining the anterior-posterior (AP) and lateral (LAT) dimensions. The $CTDI_{vol}$-to-SSDE conversion factors provided in AAPM Report 204 were derived by normalizing experimental and Monte Carlo data to patient size using tissue-equivalent material or water. In light of the expectation that tissue attenuation and the patient's geometry would provide adequate absorption information in addition to the patient's physical size information, it was necessary to take these factors into consideration. As a surrogate for the geometric approach of determining patient size, which was previously detailed in Report 204, the AAPM task group established the phrase "water equivalent diameter (D_w)" in Report 220.[14] After analyzing both approaches, there was a difference of <20%, indicating that both are reliable surrogates for patient size estimation for SSDE.[14,15]

The adoption and widespread clinical application of the robust CT dose metric, SSDE, presented a new issue to the scientific community. Furthermore, according to a particular AAPM task group, the absence of automated patient size measuring from CT scanner manufacturers could be a barrier to the implementation of SSDE.[13] Clinicians are increasingly aware of how time-consuming and laborious the manual approach is for determining patient size, which hinders the clinical use of the dose metric. While there are commercially available dose management programs that take SSDE into account, they are not cheap, and some of them have the drawback of depending on localizer image only, whereas axial CT images are preferred for determining patient size.[14,16,17] Furthermore, the effective diameter (D_{eff})-based size approach is underreported, despite a few research having tried automation employing D_w-based size measurement.[18-20] More so, only a few have compared patient size determination estimates between different methods to validate the algorithm.

Therefore, this study aimed to validate and evaluate the accuracy of a D_{eff} and segmentation-based program designed for automatic patient size and SSDE estimation in accordance with the AAPM Reports 204 and 220 guidelines. The outcome of this study is expected to yield a reliable, accurate, user-friendly, and clinically deployable algorithm for SSDE determination.

Materials and Methods

A retrospective clinical study was conducted at the Advanced Medical and Dental Institute, Universiti Sains Malaysia. The data were of CT scans performed between January 2012 and December 2021, retrieved from the center's picture archival and communication system. For the use of patient data, the study received institutional ethical committee review approval (USM//JEPeM/17120723).

Images acquisition

The study examined axial CT scans in the DICOM format from pediatric patients (aged between 1 day and 12 years) who had CT scans performed on 128-slice Siemens and 64-slice Toshiba CT machines. The reference slice positions for the patient images were the thorax (T3–T4 thoracic vertebra level), the mid-slice for head scans, and the L2–L3 lumbar vertebra level for the abdomen scan. Four CT dose index (CTDI) (polymethylmethacrylate) phantoms with known diameters (10, 14, 16, and 32 cm) representing the varying range of sizes of pediatric head and body were scanned using the Siemens CT scanner at tube voltage ranges of 80–140 kV and tube current output ranges of 100–400 mAs. The MATLAB software (version 2020A) was used to design and develop the algorithm and applications.

Automated algorithm

Automation of image contouring, segmentation, and size measurement

To segment and transform the grayscale image into a binary image while minimizing the interclass variance of the resulting thresholded black and white pixels, a global threshold and image binarization functions were first applied to the image. Then, segmentation was used to extract objects or pixels of interest and provide more precise image contour delineation. To remove distant pixels that could have an impact on the morphological image calculation and floor-fill the background, the image morphological enhancement functions were applied. The outcome is displayed in Figure 1. Rescale and masking were also used to lessen the distortion of the images caused by shadowing and gray output.

After the segmentation of the image, the LAT dimension and AP dimension of the segmented image were estimated using the appropriate functions [Figure 2]. The root product of the measured axes' values (Equation 1) was then calculated using a custom code to get the D_{eff}. The estimated D_{eff} values were pixel values and then converted to physical dimension units by extracting the DICOM tag (pixel spacing) to obtain the distance in millimeters (mm) between pixel centers in the image. The value was then multiplied by the measured pixel value to derive the equivalent length in millimeters (mm).

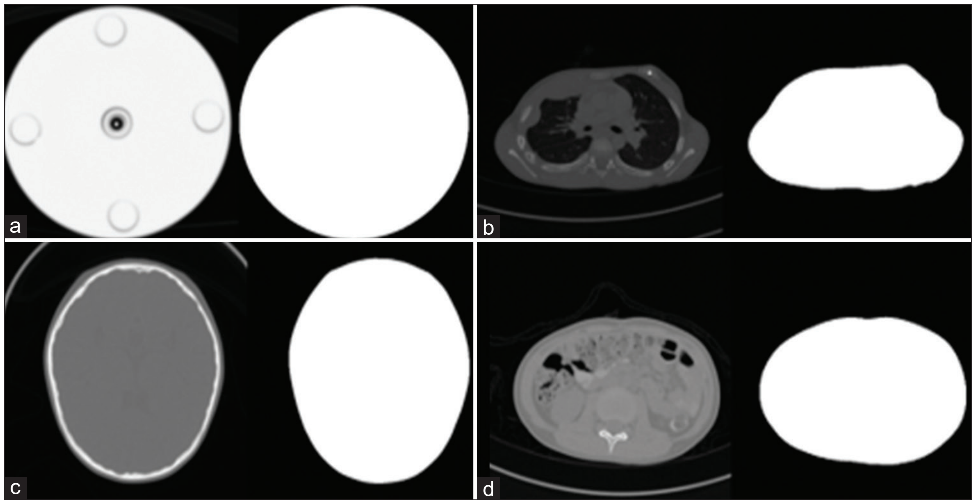

Figure 1: The left and the outcome of auto contouring using segmentation on the right. The first row shows images of a computed tomography dose index phantom (a) and patient thorax (b), while the second row shows images of patient head (c), and abdomen (d)

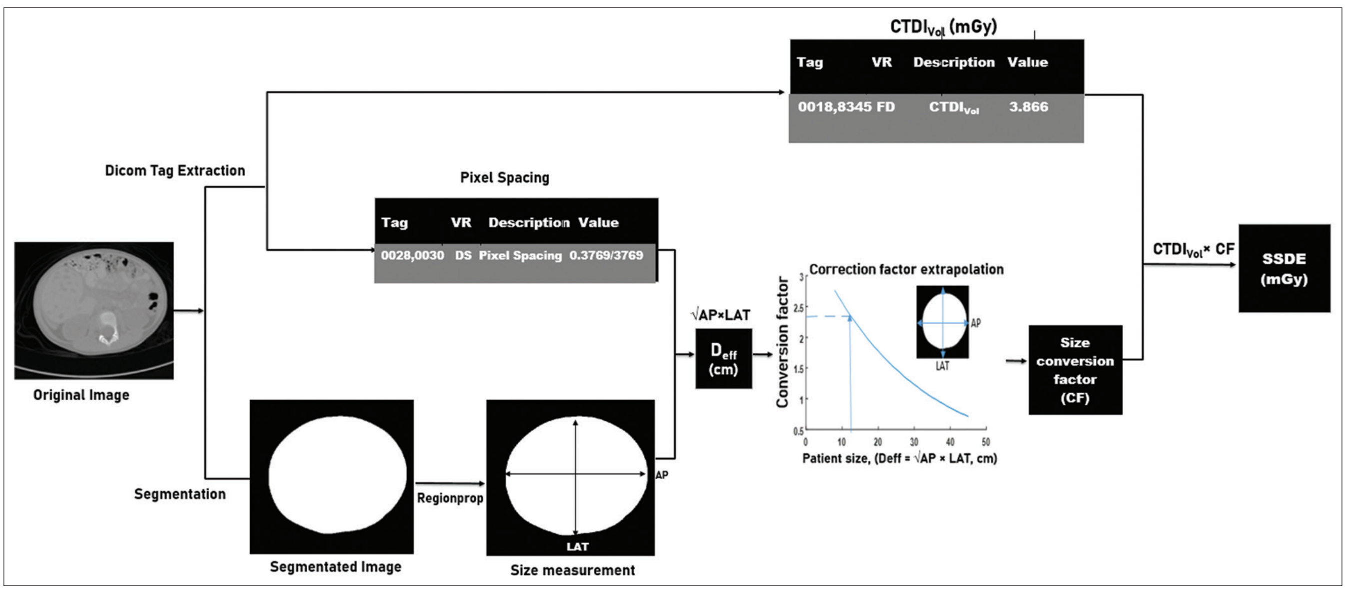

Figure 2: The flow chart for automated effective diameter and size-specific dose estimates calculation. $CTDI_{vol}$: Volume computed tomography dose index, D_{eff}: Effective diameter, AP: Anterior-posterior, LAT: Lateral

Automation of size-specific dose estimates calculation

To facilitate the automated calculation of SSDE, the algorithm generated a plot of patient size against *f*, which enables the timely extrapolation of the suitable *f* value linked to the measured patient size [Figure 1]. Next, using the unique $CTDI_{vol}$ DICOM tag recall function, the image's $CTDI_{vol}$ value was recovered. The following step involves using a mathematical function to multiply *f* by the $CTDI_{vol}$ value retrieved to calculate SSDE (mGy). Ultimately, the algorithm was moved to the MATLAB app designer's graphical user interface (GUI) to create a simple user interface for a more reliable and user-friendly application. The GUI comprises visual elements and integrated editors that facilitate programming. Pushbuttons simplify the algorithm, and there is a separate code view in the background where users can alter app functionality and behavior.

Data collection

Patient size data

For the purpose of evaluation of patient size measurement, data of the two approaches were collected: automatic and AAPM (manual). For the automated measurement, the proposed segmentation-based algorithm detailed in section 2.2 was employed. The patient's size was measured manually using the CT electronic calipers, which are described in AAPM Reports 204 and 220, respectively, for D_{eff} and D_w. For calculating the D_{eff} and D_w, the formulas in Equations 1 and 2, respectively, were used. Equation 1 depicts the determination of the D_{eff} from the AP and LAT diameters obtained from axial CT images (AAPM Report 204) while Equation 2, shows the derivation of D_w from attenuation (Hounsfield unit [HU]) and size (area) data of the image (AAPM Report 220).

$D_{eff} = \sqrt{AP \times LAT}$ Equation 1

$$D_w = 2\sqrt{\left(\frac{1}{1000}HU+1\right)\frac{A}{\pi}}$$ Equation 2

Size-specific dose estimates estimation

Both automatically and manually, SSDE was computed using Equation 3. According to Equation 3, SSDE was defined as the product of the CT scanner output dose ($CTDI_{vol}$) of the phantom size referenced for the scan and the AAPM size conversion factor (*f*). Referred for SSDE determination was the size conversion factor for the spectrum of clinical patient sizes determined from standard 16 and 32-cm reference phantoms given in the AAPM Report 204.[13]

$SSDE = CTDI_{vol\ 16,32} \times f$ Equation 3

Validation of the automated algorithm

Quantitative data of values of patient size and dose (SSDE) derived manually and automatically using the proposed algorithm were analyzed. The performance of the proposed method was first evaluated using the AAPM Report 204 method (D_{eff}-based method)[13] as the gold standard to validate the new method's performance for size and SSDE determination. It was then contrasted further with the attenuation-based patient size (D_w) calculated manually as stated in AAPM Report 220.[14] To examine discrepancies between the patient size measurement techniques, Bland–Altman plot was used.

The limits of agreement (LOA) were determined using the mean and standard deviations of the measurement differences, then the agreement between manual and automatic approaches was validated. The computation of the normalized error involved dividing the differences between the means of the methods by the mean of the automated measurement. To evaluate the strength of the linear association between measuring methods, a plot and a Pearson's correlation coefficient were estimated. In a similar vein, the percentage difference between the dose values of SSDE determined automatically and SSDE computed manually using the manually measured size was assessed.

Variability analysis was done to evaluate the accuracy of the algorithm in patient size estimation for several CT scan types or body regions (head, thorax, and abdomen) with the same level of agreement (accuracy). Besides, the degree of agreement between the measuring methods on the various CT scan types was compared.

In addition, intra-class correlation (ICC) was used to assess for intra- and inter-observer reproducibility of manual measurements of D_{eff} among the researcher and two experienced senior radiologists.

Results

A total of 80 axial CT scan images of pediatric patients' scans; 20 of which were of the head, 20 of which were of the thorax, and 40 of which were of the abdomen and four CT scan images of CTDI phantoms of known sizes were assessed for validation of the patient's size estimates and SSDE.

Validation of segmentation-based automated size measurement

The proposed segmentation-based automated algorithm method yielded a good accuracy in size measurement with an excellent agreement to the AAPM (manual) method with an error rate equal to 0.27% and 1.9% in the CTDI phantom and patient CT scan validation studies, respectively. Similarly, patient size measurement derived from the proposed algorithm and the manual measurement showed a high degree of correlation in the phantoms ($r > 0.9999$) and patient CT scan data study ($r > 0.9771$), as shown in Table 1. The LOA between methods was narrow. Table 1 shows the agreement between the methods. The Bland–Altman plot is presented in Figure 3, showing the systemic bias as the mean difference between the methods. The size determination error of this study was compared to the errors of past studies [Table 2], and the results suggest that the error of this investigation is comparable to the errors reported in earlier studies.

Validation of size-specific dose estimates calculation

Table 3 shows the validation results for the SSDE calculation. The mean SSDE value based on the manual calculation of D_{eff} is 53.37 mGy, 5.46 mGy, and 7.14 mGy for the head, thorax, and abdomen, respectively. The mean SSDE values calculated based on the proposed automated D_{eff} method are 53.97 mGy, 5.99 mGy, and 7.06 mGy for the head, thorax, and abdomen, respectively. The percentage difference between the SSDE calculated by manual and automated methods was 1%, 7%, and 1%, respectively.

Variability study

The accuracy of the proposed method varies depending on the type of CT examination or the scanned body region (head, thorax, and abdomen). The results indicate that the parameters defining the differences and agreement were narrow and small throughout all examinations [Table 1]. The CT thorax resulted in a consistently greater mean difference, LOA, and confidence interval (CI) than the head and abdomen examinations, respectively. This implies that there is the least agreement when measuring thoracic size. The mean difference across methods for the separately assessed head, thorax, and abdomen region indicates the systemic bias, as shown by the Bland–Altman plot in Figure 4.

Furthermore, an error value of 6% was found when values produced with the proposed automatic calculator were compared with D_w-based manual size estimation (RPT 220), despite the fact that a strong correlation ($r > 0.9849$) was noted, as indicated in Table 1.

Interobserver variability

Table 4 displays the findings of the ICC analysis conducted to determine the degree of agreement between the researcher's manual measurement of D_{eff} and the measurements made by two senior radiologists indicated as observers 1, 2, and

Table 1: The agreement and variability between manual and proposed algorithm size measurements in computed tomography index phantoms and different computed tomography scan types

Examination	Mean measurement based on algorithm (±SD)	Mean measurement based on manual D_{eff}/Dw (±SD)	Mean difference (±SD)	95% LOA	Pearson's correlation	Agreement (% of mean manual from algorithm)
Patient image (*n*=80)						
D_{eff}	15.5 (±3.0)	15.14 (±2.9)	−0.31 (±0.6)	−1.54–0.91	0.9835	1.9
D_w		16.50 (±3.2)	1.05 (±0.6)	−0.15–2.35	0.9849	6.0
Head (*n*=20)						
D_{eff}	14.78 (±2.0)	14.76 (±2.2)	0.02 (±0.4)	−0.68–0.92	0.9885	0.7
D_w		15.83 (±2.2)	1.05 (±0.8)	−0.62–2.62	0.9730	6.3
Thorax (*n*=20)						
D_{eff}	15.60 (±2.7)	14.92 (±2.5)	−0.67 (±0.5)	−1.62–0.27	0.9871	4.2
D_w		16.73 (±2.9)	1.13 (±0.6)	−0.18–2.40	0.9737	6.5
Abdomen (*n*=40)						
D_{eff}	15.77 (±3.5)	15.40 (±3.3)	−0.34 (±0.5)	−1.32–0.64	0.9905	2.1
D_w		16.90 (±3.7)	1.1 (±0.5)	−0.11–2.09	0.9906	6.5
Phantom (*n*=4)						
D_{eff}	18.01 (±9.6)	17.96 (±9.6)	0.052 (±0.005)	0.042–0.061	0.9999	0.27
D_w		18.93 (±10.2)	0.91 (0.54)	−0.52–1.59	0.9999	4.8

LOA: Limits of agreement, SD: Standard deviation, D_{eff}: Effective diameter, D_w: Water equivalent diameter

Table 2: Comparison of size determination error

Studies	D_{eff}		D_w	
	Percentage	cm	Percentage	cm
Cheng, 2013[22]	-	1.0	-	-
AAPM RPT 220, 2014[14]	3.54	0.80	3.00	0.70
Anam *et al.*, 2016[18]	3.89	0.90	3.26	0.77
Juszczyk *et al.*, 2021[19]	0.88	0.20	0.50	0.11
This study	1.90	0.30	6.00	1.00

D_{eff}: Effective diameter, D_w: Water equivalent diameter

3 respectively. The outcome demonstrates a high degree of measurement reliability between radiologists and the researcher. The combined average measure ICC was 0.996 with a 95% CI from 0.992 to 0.998 (F [21,42] =266.6, P < 0.001). Table 4 illustrates how closely the average measure ICC values for the head and abdomen scans when measured independently matched the combined average value.

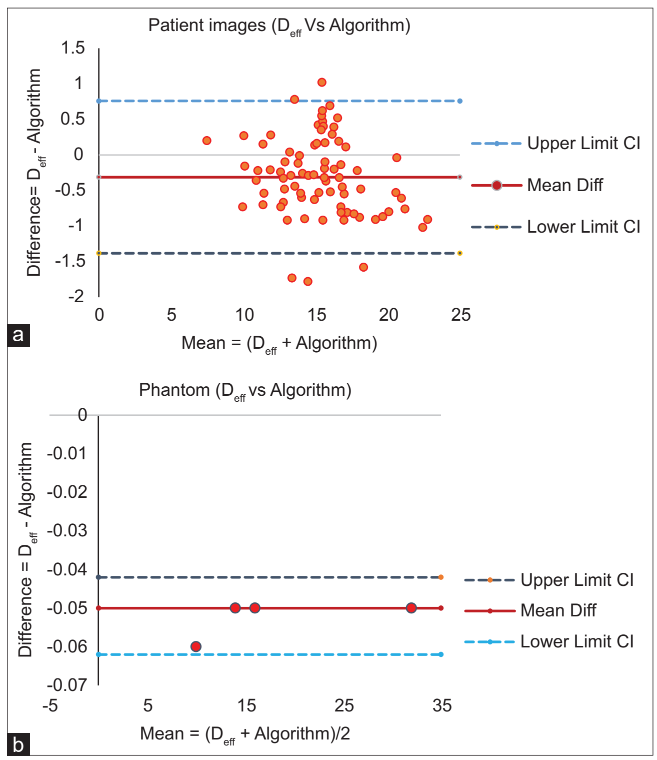

Figure 3: The Band–Altman plot of the difference between manual effective diameter and algorithm on patient computed tomography images (a) and phantoms (b). D_{eff}: Effective diameter, CI: Confidence interval

Discussion

This study showed that the proposed automated algorithm generates a reliable and accurate measurement of individual patient size (D_{eff}) and SSDE calculation. This has been supported by the small percentage error of estimation, which is 0.27% on CTDI phantoms and 1.9% on patient CT images compared with the manual AAPM 204 D_{eff} measurement as the gold standard. Therefore, this algorithm is of good accuracy and reliability since the error is within the allowed tolerance of 10% between size determination methods.[18,21] Similarly, the algorithm's accuracy in calculating SSDE was verified through a comparison with the manual estimates based on the AAPM method (AAPM Report 204). A good agreement among the methods and a 1% difference was found, indicating reasonable accuracy of the proposed automated approach in SSDE calculation for head and abdominal scans. On the other hand, a disparity of as much as 7% in proportion was noted for

Table 3: The validation of the size-specific dose estimates calculation

Examination types	Manual SSDE calculation	Automated SSDE calculation	Absolute difference	Percentage difference
Abdomen	7.14	7.06	0.08	1
Head	53.37	53.97	0.60	1
Thorax	5.46	5.99	0.44	7

SSDE: Size-specific dose estimates

Table 4: Intra-class correlation between observer's measurement

Examination/observer	ICC
Head (observers 1, 2, and 3)	ICC (10,20)=0.998
Abdomen (observers 1, 2, and 3)	ICC (10,20)=0.990
Combined (head and abdomen) (observers 1, 2, and 3)	ICC (21,42)=0.996

ICC: Intra-class correlation

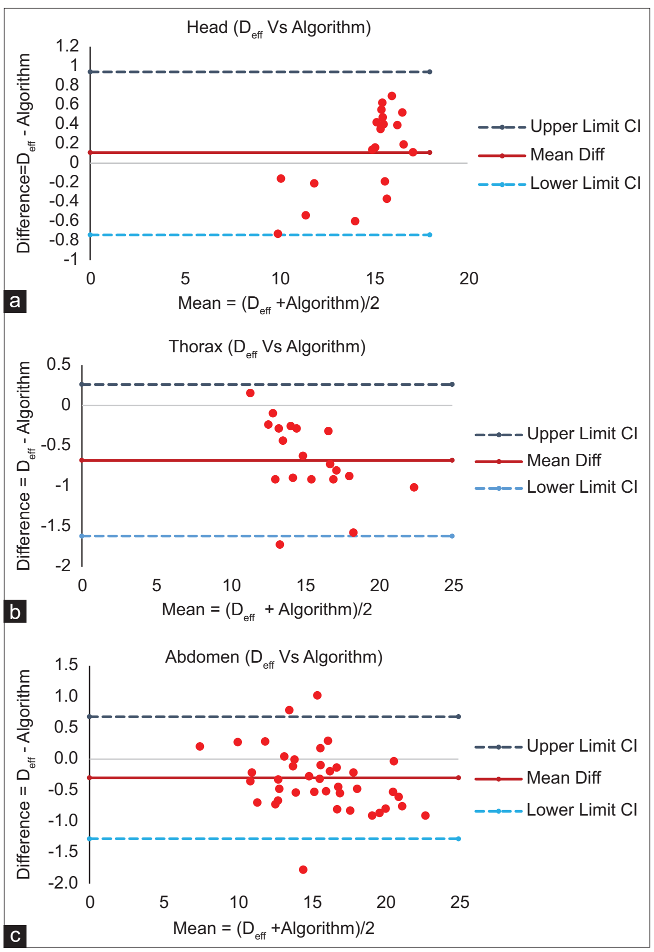

Figure 4: The Bland–Altman plot of the difference between patient size measurement derived from manual (effective diameter) compared to the algorithm measurement for computed tomography (CT) scan types (a) head CT, (b) thorax CT, (c) Abdomen CT. D_{eff}: Effective diameter, CI: Confidence interval

the thorax. However, as shown in Table 1, this is expected given the high value (4.2%) of size determination error recorded for thorax scans.

The very small error noted in the phantom study compared to that of the patient CT scan study is apparently due to the homogeneous nature of the CTDI (polymethylmethacrylate) phantoms contrasted to the heterogeneous nature of the human body contained in the patient CT scans. However, the influence of phantom inhomogeneity on SSDE may be evaluated in future study.

Besides, size determination error from this study was comparable to errors reported from similar studies.[19,22] The differences were within the acceptable 10% deviation between methods affirmed by the AAPM.[14,23] The study demography may have influenced the observed differences. Whereas, the matching studies evaluated adult subjects,[19,22] this study examined pediatric demography. Similarly, the individual variation in skill and concentration required for consistency in using the ROI tool for manual patient contour tracing may have also contributed to the observed difference.

In addition, despite being D_{eff}-based, the proposed method in this study produced an inaccuracy of roughly 6% when compared to the manually determined D_w-based size that is detailed in AAPM Report 220. However, this is to be expected given the intrinsic, albeit negligible, distinction between D_{eff} and D_w. Moreover, it has been shown that using either approach did not result in a statistically significant change in the SSDE.[24] Furthermore, this is a major strength of this study since the proposed segmentation-based automatic calculator estimations of SSDE are reliable regardless of the two recommended size surrogates (D_{eff} and D_w).

Furthermore, the findings of this study demonstrate agreement between the attenuation-based D_w and geometric-based D_{eff}, which is consistent with the AAPM affirmation. According to the current study's findings, a comparison between the manual D_{eff}-based size and the manual D_w-based size, and the proposed segmentation-based automated method yields a high positive Pearson's correlation with nearly equal magnitudes (D_{eff}: 0.9673, D_w: 0.9701). This suggests that the two methods can be used interchangeably with confidence. Furthermore, this is consistent with the results of the AAPM task group.[14]

Furthermore, this study showed that D_{eff} enabled segmentation-based automation of patient size measurement in several CT scan types, with a difference of <10% from the D_w equivalent. The automation of the D_{eff}-based patient size estimator for SSDE has not been published as frequently as the automation of the D_w-based size and SSDE estimator,[22] despite the fact that the evidence that is currently available suggests that D_w and D_{eff} do not differ significantly.[18,19,24] Therefore, as the closest substitute for D_w, the D_{eff} approach should not be overlooked but should instead be further investigated. Furthermore, compared to attenuation data, patient geometric data are practically easily acquired, hence, more readily available, and simpler to estimate than attenuation, D_w.

Comparatively, this study estimated systemic bias and the limits of agreement associated with measurement methods, in contrast to prior studies [Table 1 and Figures 2, 3]. In addition, comparing the algorithm's performance with the examination or scan type reveals good error of determination and accuracy for the head, thorax, and abdomen CT scan types. The variances were within or <10% tolerance. However, the CT scan of the head exhibited the highest agreement, followed by the CT scan of the abdomen, and the CT scan of the thorax had the lowest.

In addition, the variability amongst observers in obtaining the D_{eff} measurement demonstrated a strong correlation between them. Likewise, the measurements exhibited high agreement since the values obtained by the observers did not differ significantly from zero. We suggest that the radiologist's experience, the CT electronic caliper's ease of use, and the AAPM Report 204's precise definitions and procedures for the D_{eff} measurement are what caused the observed agreement. Besides, interobserver agreement is commonly found in investigations including measuring system analysis and biophysical measurements, according to earlier research.[25,26]

One of the study's drawbacks is that it only examined data from pediatric patients because they are the most critical patient group with regard to ionizing radiation effects. Therefore, the results might not apply to adult demographics in general. Adult CT images may need additional image morphological augmentation because of shadowing, a higher degree of gray output, and a broader field of view. Therefore, further study may be required to evaluate the accuracy of the algorithm in adult CT scans. In addition, since DICOM is the only medical image format that is free of deterioration from image compression and conversion, the proposed segmentation-based algorithm is only compatible with DICOM image formats.

Conclusion

In accordance with the AAPM methodology, this study developed an automated system that can measure the size of individual patients using image segmentation and calculate SSDE. The results demonstrate that the algorithm yields minimal measurement errors, validating that it generates accurate and reliable measurements of patient size and size-specific dose estimations. In addition, the outcome affirms that D_{eff} is a reliable surrogate for D_w when determining a patient's size for SSDE.

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Nil.

Conflicts of interest

There are no conflicts of interest.

References

1. Kost SD, Fraser ND, Carver DE, Pickens DR, Price RR, Hernanz-Schulman M, *et al.* Patient-specific dose calculations for pediatric CT of the chest, abdomen and pelvis. Pediatr Radiol 2015;45:1771-80.
2. Almohiy H. Paediatric computed tomography radiation dose: A review of the global dilemma. World J Radiol 2014;6:1-6.
3. Miglioretti DL, Johnson E, Williams A, Greenlee RT, Weinmann S, Solberg LI, *et al.* The use of computed tomography in pediatrics and the associated radiation exposure and estimated cancer risk. JAMA Pediatr 2013;167:700-7.
4. NCRP Report 160 – NCRP | Bethesda, MD. Available from: https://www.ncrponline.org/publications/reports/ncrp-report-160-2/. [Last accessed on 2023 Jan 04].
5. McCollough CH, Leng S, Yu L, Cody DD, Boone JM, McNitt-Gray MF. CT dose index and patient dose: They are not the same thing. Radiology 2011;259:311-6.
6. Strauss KJ, McKenney SE, Brady SL. Improved estimates of trunk and head CT radiation dose: Development of size-specific dose estimate. J Am Coll Radiol 2020;17:560-2.
7. Turner AC, Zankl M, DeMarco JJ, Cagnon CH, Zhang D, Angel E, *et al.* The feasibility of a scanner-independent technique to estimate organ dose from MDCT scans: Using CTDIvol to account for differences between scanners. Med Phys 2010;37:1816-25.
8. Turner AC, Zhang D, Khatonabadi M, Zankl M, DeMarco JJ, Cagnon CH, *et al.* The feasibility of patient size-corrected, scanner-independent organ dose estimates for abdominal CT exams. Med Phys 2011;38:820-9.
9. McMillan K, Bostani M, Cagnon C, Zankl M, Sepahdari AR, McNitt-Gray M. Size-specific, scanner-independent organ dose estimates in contiguous axial and helical head CT examinations. Med Phys 2014;41:121909.
10. Moore BM, Brady SL, Mirro AE, Kaufman RA. Size-specific dose estimate (SSDE) provides a simple method to calculate organ dose for pediatric CT examinations. Med Phys 2014;41:071917.
11. Garzón WJ, Aldana DF, Cassola VF. Patient-specific organ doses from pediatric head CT examinations. Radiat Prot Dosimetry 2020;191:1-8.
12. Franck C, Smeets P, Lapeire L, Achten E, Bacher K. Estimating the patient-specific dose to the thyroid and breasts and overall risk in chest CT when using organ-based tube current modulation. Radiology 2018;288:164-9.
13. Boone JM, Strauss KJ, Cody DD, McNitt-Gray MF, Toth TL. American Association of Physicist in Medicine AAPM, Report No. 204: Size-Specific Dose Estimates in Pediatric and Adult Body CT Examinations. MD; 2011.
14. McCollough C, Bakalyar DM, Bostani M, Brady S, Boedeker K, Boone JM, *et al.* Use of water equivalent diameter for calculating patient size and size-specific dose estimates (SSDE) in CT: The report of AAPM task group 220. AAPM Rep 2014;2014:6-23.
15. Boone JM, Strauss KJ, Hernandez AM, Hardy A, Applegate K, Artz N, *et al.* American Association of Physicist in Medicine AAPM, Report No. 293:Size-Specific Dose Estimate (SSDE) for Head CT. Alexandria, VA; 2019.
16. Leng S, Shiung M, Duan X, Yu L, Zhang Y, McCollough CH. Size-specific dose estimates for chest, abdominal, and pelvic CT: Effect of intrapatient variability in water-equivalent diameter. Radiology 2015;276:184-90.
17. Pourjabbar S, Singh S, Padole A, Saini A, Blake MA, Kalra MK.

Size-specific dose estimates: Localizer or transverse abdominal computed tomography images? World J Radiol 2014;6:210-7.
18. Anam C, Haryanto F, Widita R, Arif I, Dougherty G. Automated calculation of water-equivalent diameter (DW) based on AAPM task group 220. J Appl Clin Med Phys 2016;17:320-33.
19. Juszczyk J, Badura P, Czajkowska J, Wijata A, Andrzejewski J, Bozek P, *et al.* Automated size-specific dose estimates using deep learning image processing. Med Image Anal 2021;68:101898.
20. Wu J, Han RP, Liu YL. Using a somatosensory controller to assess body size for size-specific dose estimates in computed tomography. Biomed Res Int 2018;2018:2734297.
21. Bostani M, McMillan K, Lu P, Kim HJ, Cagnon CH, DeMarco JJ, *et al.* Attenuation-based size metric for estimating organ dose to patients undergoing tube current modulated CT exams. Med Phys 2015;42:958-68.
22. Cheng PM. Automated estimation of abdominal effective diameter for body size normalization of CT dose. J Digit Imaging 2013;26:406-11.
23. Dio P, Anam C, Hidayanto E, Sutanto H, Asiah R, Fatichah L, *et al*. Evaluation of radiation dose accuracy calculated using IndoseCT software with direct measurement on polyester-resin phantoms. Radiat Phys Chem 2022;201:110473.
24. Abdulkadir MK, Shuaib IL, Nasirudin RA, Samsudin AH, Osman ND. Comparison between D_{eff} and D_w approaches for estimation of size-specific dose in paediatric CT imaging. Radiat Phys Chem 2022;198:110205.
25. Popović ZB, Thomas JD. Assessing observer variability: A user's guide. Cardiovasc Diagn Ther 2017;7:317-24.
26. Ohagwu CC, Onoduagu HI, Eze CU, Ochie K, Ohagwu CI. Intra-and inter-observer reproducibility study of gestational age estimation using three common foetal biometric parameters: Experienced versus inexperienced sonographer. Radiography 2015;21:54-60.