CAN THE SIZE-SPECIFIC DOSE ESTIMATE BE DERIVED FROM THE BODY MASS INDEX? A FEASIBILITY STUDY

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Received 15 November 2021; revised 10 February 2022; editorial decision 3 March 2022; accepted 3 March 2022

Size-specific dose estimate (SSDE) index appears to be more suitable than the commonly used volume computed tomography dose index (CTDIvol) to estimate the dose delivered to the patient during a computed tomography (CT) scan. We evaluated whether an SSDE BMI can be determined from the patient’s body mass index (BMI) with sufficient reliability in the case that a SSDE is not given by the CT scanner. For each of the three most used examination types, CT examinations of 50 female and 50 male patients were analyzed. The SSDE values automatically provided by the scanner were compared with SSDE BMI determined from CTDIvol and BMI. A good accordance of SSDE BMI and SSDE was found for the chest and abdominal regions. A low correlation was observed for the head region. The presented method is a simple and practically useful surrogate approach for the chest and abdominal regions but not for the head.

INTRODUCTION

The volumetric computed tomography dose index (CTDIvol) and the associated dose length product (DLP) are routine dosimetry metrics that are currently used to monitor radiation exposure to patients undergoing computed tomography (CT)1,2. However, CTDIvol is of limited value as it does not represent the amount of exposure an individual patient receives but only indicates the amount of radiation that a cylindrical polymethyl-methacrylate (PMMA) phantom with a diameter of either 16 cm or 32 cm would receive3–5. For this reason, the size-specific dose estimate (SSDE) index was introduced, which incorporates the water-equivalent skin-to-skin diameter of the patient6,7. This methodology is an IEC standard since 20198.

The advantage of SSDE is that individual patient size is used to estimate the dose. This is an important feature because CTDIvol, which is independent of patient size and scan length, would indicate too low a dose for a selected examination in slim patients, while it would be the opposite in obese patients. Dose management systems are currently being established to report radiation exposure for further evaluation when diagnostic reference values are significantly exceeded without reason9. Improved estimates of the exposure are certainly necessary to automatically and reliably identify unjustified high doses of radiation. For the latter, SSDE seems well suited because it is patient size-specific.

However, the calculation of the SSDE may fail if the patient’s body contour cannot be clearly identified in the overview images or is outside of the overview images and the diameter in the center slice is therefore incorrectly determined or not determined at all. Although methods have been developed which recognize these problems and improve the calculations, they have not yet been implemented in the scanners currently in use10. In addition, the calculation of the diameter and thus the SSDE from all CT slices is time-consuming and only possible afterward11.

Therefore, it seems an interesting approach to estimate the SSDE without information about the water-equivalent diameter of the patient. Although other research groups have already addressed this issue, they have done so with different approaches, most of which did not differentiate by gender or include pediatric patients12–16. Several research groups already addressed the correlation of body mass index (BMI) and water-equivalent diameter but considered only a specific body region, limited themselves to individual types of CT examination or compared results from different scanners.

In this study, we evaluate a simple approach for female and male patients using BMI to estimate the SSDE. BMI is readily available and can often be
retrieved from the hospital information system to estimate SSDE from CTDI\textsubscript{vol} for the most frequently examined body regions of head, chest and abdomen. When CT scanners and dose management systems do not provide this value, this could be beneficial.

**MATERIALS AND METHODS**

This retrospective study complies with the Declaration of Helsinki and was carried out with the approval of the Ethics Committee of the Friedrich Schiller University Jena. All patients provided written informed consent.

**Patient population**

For each of head, chest and abdomen, 100 CT examinations were retrospectively selected from the hospital database for 50 female and 50 male adult patients (see Table 1). The sample size was chosen to obtain a reasonable statistical result with a reasonable amount of information collection. The biometric data for calculating the BMI were taken from the electronic health records and were not from the period of 2 weeks before to 2 weeks after the examination. None of the patients had any prosthesis or other implants within the scan field. The baseline patient data and the scan parameters are summarized in Table 1.

**Technical specification**

All scans had been performed with the same CT scanner (Revolution CT, General Electric Company, USA), which automatically provides CTDI\textsubscript{vol} and SSDE. The scanner is a 256 slice system and has a patient coverage in \textit{z}-direction of up to 160 mm, resulting in 0.625 mm thickness per detector element.

CTDI\textsubscript{vol} and DLP were determined by the scanner for patient-mimicking cylindrical PMMA phantoms with diameter of 16 and 32 cm for the head and body regions, respectively\textsuperscript{(3)}. By contrast, the American Association of Physicists in Medicine (AAPM) Report 220 proposes to use the patient’s effective water-equivalent diameter, \(D_W\), which can be extracted from localizer images in lateral and anterior–posterior directions or from cross-sectional CT images to calculate SSDE\textsuperscript{(7)}. The scanner used in our work calculates \(D_W\) as

\[
D_W = \sqrt{\text{LAT} \cdot \text{AP}}
\]  
(1)

using the patient’s diameter in lateral direction, LAT, and in anterior–posterior direction, AP, as illustrated on a central slice of an exemplary scan region (center-slice method) in Figure 1.

In the AAPM Report 220, conversion factors, \(f(D_W)\), are available for both PMMA phantoms for values of \(D_W\) in the range from 8 to 45 cm to calculate SSDE from the CTDI\textsubscript{vol} values output from the scanner:

\[
\text{SSDE} = \text{CTDI}_{\text{vol}} \cdot f(D_W)
\]  
(2)

The conversion factors, \(f(D_W)\), are based on a curve fit between physical measurements and Monte Carlo simulations\textsuperscript{(6, 7)}. However, in cases where \(D_W\) is not automatically calculated, we propose a simple method to derive SSDE from the patient’s BMI and the CTDI\textsubscript{vol} output from the scanner, where the metric, SSDE\textsubscript{BMI} (index BMI indicates calculation based on the patient’s individual BMI) is calculated as follows:

\[
\text{SSDE}_{\text{BMI}} = \text{CTDI}_{\text{vol}} \cdot f(BMI)
\]  
(3)

The BMI was calculated according to the equation

\[
\text{BMI} = \frac{\text{Weight}}{\text{Height}^2}.
\]  
(4)

To determine the conversion factors \(f(D_W)\) used by our CT scanner, the ratios between the available SSDE and CTDI\textsubscript{vol} values were calculated for all patients in each anatomic group (i.e. head, chest, and abdomen):

\[
f(D_W) = \frac{\text{SSDE}}{\text{CTDI}_{\text{vol}}}
\]  
(5)

In addition to Report 220, the AAPM released Report 293 for head CT\textsuperscript{(17)}. The conversion factor, \(f(D_W)\), is calculated there with the formula

\[
f(D_W) = 1.9852 \cdot e^{-0.0486\cdot D_W}
\]  
(6)

Most of the currently used scanners calculating the SSDE still according to AAPM Report 220 for the head section, so we decided to consider both approaches for the head section for this work.

A similar functional relationship to the BMI was not automatically calculated, we propose a simple method to derive SSDE from the patient’s BMI and the CTDI\textsubscript{vol} output from the scanner, where the metric, SSDE\textsubscript{BMI} (index BMI indicates calculation based on the patient’s individual BMI) is calculated as follows:

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A similar functional relationship to the BMI has now been examined. The approach should work if \(D_W\) and BMI are linearly related. This was initially checked visually as shown using a scatterplot. To distinguish, the conversion factor is now referred to as \(f(BMI)\). To determine the functions for \(f(BMI)\) for each group, the calculated gender-separated values \(f(D_W)\) (\(n = 50\) each) were plotted against the corresponding individual BMI values and were then fitted.
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Table 1. Baseline patient data and scan parameters.

|              | Female (n = 50) | Male (n = 50) | Scan parameter |
|--------------|----------------|--------------|----------------|
| **Head**     |                |              |                |
| Age          | 66.4 ± 14.1    | 67 ± 15.5    | Tube voltage (kVp) | 120 |
| BMI          | 26.7 ± 5.9     | 26.4 ± 4.7   | Effective mAs (mean) | 313 |
| CTDI         | 53.8 ± 6.6     | 52.9 ± 4.4   | Detector coverage (mm) | 80  |
| SSDE (CT)    | 49.8 ± 5.6     | 48.2 ± 4.0   | Table increment (mm) | 80  |
|              | 40.3–73.4      | 39.7–57.2    | Scanmode | Step and shoot, axial |

|              | Female (n = 50) | Male (n = 50) | Scan parameter |
|--------------|----------------|--------------|----------------|
| Age          | 64.6 ± 12.4    | 65.1 ± 12.1  | Tube voltage (kVp) | 120 |
| BMI          | 26.8 ± 5.6     | 27.1 ± 4.0   | Effective mAs (mean) | 96  |
| CTDI         | 5.0 ± 2.8      | 6.8 ± 2.4    | Detector coverage (mm) | 80  |
| SSDE (CT)    | 5.1 ± 2.1      | 6.5 ± 1.7    | Pitch factor | 0.99 |
|              | 2.6–9.4        | 3.3–9.6      | Scanmode | Spiral |

|              | Female (n = 50) | Male (n = 50) | Scan parameter |
|--------------|----------------|--------------|----------------|
| Age          | 66.2 ± 12.0    | 66.1 ± 10.9  | Tube voltage (kVp) | 120 |
| BMI          | 24.4 ± 4.9     | 27.0 ± 5.6   | Effective mAs (mean) | 109 |
| CTDI         | 6.4 ± 1.8      | 8.6 ± 3.2    | Detector coverage (mm) | 80  |
| SSDE (CT)    | 7.2 ± 1.1      | 8.4 ± 1.8    | Pitch factor | 0.99 |
|              | 5.7–9.8        | 5.8–12.7     | Scanmode | Spiral |

Table 1. Baseline patient data and scan parameters.

|              | Female (n = 50) | Male (n = 50) | Scan parameter |
|--------------|----------------|--------------|----------------|
| Age          | 66.4 ± 14.1    | 67 ± 15.5    | Tube voltage (kVp) | 120 |
| BMI          | 26.7 ± 5.9     | 26.4 ± 4.7   | Effective mAs (mean) | 313 |
| CTDI         | 53.8 ± 6.6     | 52.9 ± 4.4   | Detector coverage (mm) | 80  |
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|              | 40.3–73.4      | 39.7–57.2    | Scanmode | Step and shoot, axial |

Table 1. Baseline patient data and scan parameters.

where \( f(BMI) = m \cdot e^{b \cdot BMI} \) (7)

where \( m \) and \( b \) are fit parameters. MATLAB 2017a was used for these curve fits to extract the values of \( m \) and \( b \) for both genders and each target region (see Figure 4). With known parameters \( m \) and \( b \), the fit function can be used to later calculate SSDE\textsubscript{BMI} from BMI according to Eq. (3).

**Statistical analysis**

To assess the validity of our approach, the SSDE\textsubscript{BMI} values were compared to the corresponding SSDE values by calculating the coefficient of determination \( R^2 \) of the linear fit through the point of origin. A coefficient of determination of \( \geq 0.25 \) was classified as weak correlation, \( \geq 0.5 \) as moderate and \( \geq 0.75 \) as substantial correlation\textsuperscript{18}.

In addition, Bland–Altman diagrams were created to show the variation in the results. For this purpose, the mean of two corresponding values (SSDE and SSDE\textsubscript{BMI}) was plotted against the difference of the two values. For normally distributed differences, one would expect 95% of the differences to lie between two lines, calculated as

\[
\bar{d} \pm 1.96 \cdot \text{SD}(d)
\]

(8)

where \( d \) is the difference between SSDE and SSDE\textsubscript{BMI}, and \( \bar{d} \) denotes the mean of all individual \( d \) for each target region and gender. Almost all pairs

Figure 1. Localizer images for an abdominal scan; the black lines show the diameter of the patient in the central slice position; left: lateral direction (LAT); right: anterior–posterior direction (AP); the SSDE values output by the CT scanner used in this study are calculated using this center-slice method.
of calculation of the two methods should ideally be closer to each other than these extreme values, which are called the ‘95% limits of agreement’ (19).

RESULTS

Figure 2 shows the distributions of the water-equivalent diameter $D_W$ determined by CT and BMI for all examinations. As expected, the values for $D_W$ for the head are distinctly less scattered compared to the corresponding values for BMI, indicating the low correlation between head diameter and BMI.

Figure 3 shows the scatterplots between $D_W$ and BMI for the different body regions together with the linear regression lines. From these graphs, as well as from the $R^2$ values of the linear fit functions, the poor correlation in the head region between $D_W$ and BMI is clear. In order to show to what extent this affects the calculation of the SSDE, we have nevertheless continued the evaluation for the head region. The linear correlation is moderate for both the thoracic and abdominal regions, with a slightly better fit for the abdominal region in female patients and for the thoracic region in male patients.

Figure 4 shows the scatterplots between the conversion factors $f(D_W)$ derived from Eq. (5) and the corresponding BMI for all patients and body regions together with the fit curves according to Eq. (7). The coefficients of determination $R^2$ of the fit functions between $f(D_W)$ and BMI are also given for each equation. All results for chest and abdomen can be classified as moderate correlation. The fit result is best for the abdominal region in females and is best for the chest region in males. For the head region, the results corroborate the expected missing correlation between the conversion factors $f(D_W)$ and BMI. The results for estimations according to the older AAPM Report 220 are reproduced in gray color. Comparing the $R^2$, we see that the current recommendation of the AAPM to calculate the $f(D_W)$ with the method described in Report 293 does not improve the results with our method. Although the use of $R^2$ is not optimal for non-linear models, as it then often simulates better results, it is still a quick and easy way to get an initial overview by comparing data series (20).

In Figure 5, the results for the calculated SSDE$_{BMI}$ are compared with the SSDE. Correlations for the head region are again worst but can be classified as moderate. Although the previous findings of this study tend to suggest that the abdomen region might give the best results in the female group. Looking at $R^2$ between SSDE$_{BMI}$ and SSDE, it shows an substantial result in the chest region and only a weak correlation of both values for the abdominal region. The result of the assessment of the SSDE$_{BMI}$ for the male group is substantial in the chest region and is moderate for the abdominal region.

As seen in Figure 6, 95% of the cases lie within the boundary lines (i.e. two to three values in this case) for all study groups. Thus, when assessing the results using this method, one can assume that an approximation of the SSDE with the help of the BMI is quite practicable even for the head region. In view of the previous results, however, this should be questioned critically.
**DISCUSSION**

The proposed method is a quick and easy alternative to evaluate size-specific doses for patients with conspicuous CTDIvol values in situations where an automatically calculated SSDE is not provided by the CT scanner. It is not a substitute for an exact calculation, as recommended in the AAPM report, but can help physicians or radiographers to estimate the acceptability of an applied dose considering a reference level.

An advantage of our approach is that it uses the BMI in combination with derived equations for different body regions without the need to know the patient’s effective diameter. However, this approach is also limited because the BMI for a small person (child or small adult) could be the same as for a tall person, while the effective diameter and thus the exposed volume would most likely be significantly different. Parikh et al. investigated the extent to which body weight can also be used to determine SSDE in pediatric patients. The results differ depending on the patient’s body diameter.(5) Therefore, to improve the approximation of our proposed SSDE_{BMI} to SSDE, more patients and groups including pediatric patients need to be investigated in future studies.(21) Furthermore, the ratio of BMI to \( D_w \) can vary, depending on the proportions of muscle and fat tissue present and is age and gender effected.(22) These differences can also affect the correct estimation of the SSDE_{BMI} . Another uncertainty for the calculated BMI is possible weight loss, especially in oncology and intensive care patients, during the maximum allowable 2-week period between weight and height data collection and CT acquisition.

Considering only the Bland–Altman method to evaluate the results, one could come to the conclusion that the estimation of SSDE values for the head based on BMI is unproblematic. However, in comparison with the other results, we cannot recommend this. The lack of correlation between \( D_w \) and BMI in the area of the head is particularly evident in Figure 3. The coefficient of determination here is slightly better for men than for women, but both values are extremely poor and show that a calculation using our method cannot produce any useful values for SSDE_{BMI} in the head region. There are recommendations to determine SSDE using specialized head scan band regardless of size and/or weight.(23) For the head region, the equations used in our study to calculate \( f(BMI) \)
Figure 4. Scatterplots between BMI and $f(D_{W})$ for all target regions; the lines indicate the fit to the data; the formulas developed of these fits can be used to calculate $f(BMI)$ from the BMI data of the patients; for the diagrams of the head section, light gray is the data set calculated according to AAPM 220, black stand for calculations with conversion factors as described in AAPM Report 293.

show strikingly poor agreement with the values of $f(D_{W})$, which is reflected in the low values for $R^2$ (see Figure 4). The changes in AAPM Report 293 compared to Report 220 have only a small effect on our findings. It appears that estimating SSDE values of the head region from a patient’s BMI is not accurate. As Figure 2 shows, the diameter of the head has only small variations in patients, although the BMI varies relatively strongly, resulting in weak or no correlation. This observation is also supported by a study by Alikhani et al., who used an exponential relationship to calculate a size-specific $f_{size}$ from BMI and assumed independence of both values for the head region\(^{(12)}\). Mehdipour et al. have investigated how SSDE and lateral body diameter correlate. The correlation for the abdominal and for the chest region they found are also seen in our investigations. However, they did not include gender in their study, where our results show a difference between female and male patients\(^{(15)}\). Xu et al. found that the BMI is better suited than body weight to estimate SSDE. However, they calculated the SSDE from the patients water-equivalent diameter estimated from body weight and BMI\(^{(16)}\). In our study, we directly estimated the SSDE\(_{\text{BMI}}\) from the BMI.

The results presented in Figure 5 show moderate correlations between SSDE\(_{\text{BMI}}\) and SSDE for the abdominal region. The best agreement with a substantial correlation was observed for the chest region, suggesting that BMI for this region predicts SSDE well. The correlations established with the scatters in Figure 4 provide feasible approaches for calculating SSDE in the chest and abdominal regions with almost similar accuracy as in the AAPM report. O’Neill et al. also investigated the applicability of BMI to estimate the individual patient radiation dose by calculating an effective diameter from the BMI and demonstrated a substantial correlation ($r = 0.88$) between these two values\(^{(13)}\). However, they only evaluated abdominal scans in 50 patients (female and male varied) in their study.

Discrepancies between SSDE\(_{\text{BMI}}\) and SSDE may also be caused by the method implemented in the CT scanner to determine the effective diameter. The scanner used in our study determines the effective diameter from the central position of the scout images (see
Figure 5. Scatterplots between SSDE_{BMI} and SSDE for all three anatomic target regions and both gender; the black dashed lines represent the lines of identity; $R^2$ stands for the determination coefficients between SSDE_{BMI} and SSDE; for the diagrams of the head section, light gray is the data set calculated according to AAPM 220, black stand for calculations with conversion factors as described in AAPM Report 293.

Figure 1), as described in the AAPM Task Group 204 report\(^6\). Because of its higher accuracy, the AAPM recommends calculating $D_W$ using the slice-by-slice method from axial CT images\(^7, 24, 25\). However, the disadvantage of the latter method is the longer calculation time and that the results are obtained only retrospectively. In most cases, $D_W$ calculated by the center-slice method is almost identical to the $D_W$ calculated by the slice-by-slice method, although it has been shown that they can differ by up to 3.7% in abdominal phantom studies\(^7\). In patients, it could be even larger because the shape of the abdominal region varies more depending on weight, height and individual constitution. Boos et al. showed that the center-slice method results in a mean relative absolute error of 2–5% in pediatric and adult abdominal and chest CT compared with the slice-by-slice method\(^14\). For pediatric thoracic, abdominal and pelvic scans, Öszoykal et al. determined a root-mean-squared error of 1.2–11% when comparing the SSDE from the center-slice method with the slice-by-slice determination\(^26\). Furthermore, SSDE also depends on the positioning of the patient in the isocenter of the scanner gantry, which can lead to inaccuracies if performed incorrectly\(^7, 27, 28\). The IEC standard for SSDE cites an included neck in the scanned anatomy, an actual scan length that exceeds the range of the overview radiogram, unilateral or bilateral limb scans or foreign objects located in the scan field as possible causes of miscalculation of the SSDE by the scanner software\(^8\). These facts illustrate that the values for SSDE adopted as reference in our study also need to be reviewed and carefully evaluated.

In general, the use of SSDE is very helpful and diagnostic reference levels should be set to SSDE instead of CTDI\(_{vol}\). Although the CTDI\(_{vol}\) is a useful indicator of radiation dose, it does not represent the dose received by the patient due to the neglect of size. Therefore, in very slim or obese patients, the CTDI\(_{vol}\) should be compared with the SSDE to check the plausibility of the CTDI\(_{vol}\) value output by the scanner. For the optimization process of various CT examinations, the SSDE is an important variable for adapting the radiation exposure to as many body constitutions as possible. As described by Lyra et al.\(^29\), there is only a low correlation between the
Figure 6. Bland–Altman-diagrams comparing SSDE and SSDE\(_{\text{BMI}}\); the dots represent the result of a corresponding pair of SSDE and SSDE\(_{\text{BMI}}\); the solid lines indicate the mean of the differences between corresponding SSDE and SSDE\(_{\text{BMI}}\), and the dashed lines represent the mean of the difference plus or minus 1.96 multiplied with the standard deviation of the differences; for the diagrams of the head section, light gray is the data set calculated according to AAPM 220, black stand for calculations with conversion factors as described in AAPM Report 293.

The effective dose calculated with the DLP compared to the SSDE. It can therefore be assumed that the value for the effective dose calculated from \(\text{CTDI}_{\text{vol}}\) and DLP should also be critically examined, especially for patients in whom \(\text{CTDI}_{\text{vol}}\) and SSDE differ greatly from one another.

**CONCLUSION**

A patient's BMI can be used in CT scans of the chest and the abdomen to efficiently estimate SSDE. This SSDE\(_{\text{BMI}}\) has an almost similar accuracy to that derived from images. For CT imaging of the skull or brain, using BMI does not show good accuracy because the effective diameter of the head does not vary much in adults. When calculation of the SSDE from images is not possible, e.g. because body parts of the patient are not included in the image or localizer images, or because of missing software to calculate SSDE, the proposed methodology of using BMI can be applied.

**ACKNOWLEDGEMENTS**

Not applicable.

**FUNDING**

The authors state that this work has not received any funding.

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