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Volume computed tomography dose index ($CTDI_{vol}$) and size-specific dose estimate (SSDE) for tube current modulation (TCM) in CT scanning

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► ***Original article***

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ABSTRACT

Background: In the tube current modulation (TCM) technique, tube current is changed dynamically during the scanning process. To quantify the effect of a dynamic tube current, a distinct calculator is needed to estimate the CT output radiation dose in terms of volume CT dose index ($CTDI_{vol}$) and individual patient dose in terms of size-specific dose estimate (SSDE). This study developed a specific calculator for CT scanning using the TCM technique. ***Materials and Methods:*** The tube current was extracted from the DICOM header for every slice, and averaged over the scan length. The water equivalent diameter (D_w) and SSDE values were calculated for each tube rotation. The software was retrospectively applied to 57 patients who had undergone abdominal and thoracic CT examinations using a multi-detector CT, the Somatom Emotion 6. ***Results:*** The differences between the calculated $CTDI_{vol}$ and the $CTDI_{vol}$ reported by the CT scanner were 4.4 ± 1.2% and 6.0 ± 2.0% for abdominal and thoracic examinations, respectively. The average tube current was found to be linearly correlated with D_w with R^2 values of 0.707 and 0.696 for abdominal and thoracic examinations, respectively. The average tube current was also linearly and strongly correlated with the SSDE with R^2 values of 0.941 and 0.887 for abdominal and thoracic examinations, respectively. ***Conclusion:*** Calculator for estimating $CTDI_{vol}$ and SSDE specifically for TCM in CT scanning has been successfully developed. The difference between calculated $CTDI_{vol}$ values using this calculator and reported $CTDI_{vol}$ values were less than 10%.

Keywords: *Volume CT dose index ($CTDI_{vol}$), size-specific dose estimate (SSDE), water equivalent diameter (D_w), tube current modulation (TCM).*

INTRODUCTION

The use of CT scanners is continually increasing (1, 2), because they provides high quality image in 3D (3) with very fast acquisition time (4). The quality of the images are characterized by high spatial resolution, low noise level, and high contrast to differentiate between different tissues (5). CT scan is considered a powerful modality, but unfortunately it contributes most of the medical dose experienced by patients. The International Atomic Energy Agency (IAEA) reported that CT scans were used for approximately 25% of all radiological examinations and contributed to approximately 60 to 70% of the total dose from radiological examinations (1). Bauhs *et al.* (6) reported that the effective dose from a thoracic CT examination was about 5-7 mSv, while the effective dose from a conventional thoracic X-ray examination was only 0.1-0.2 mSv. It is well known that the risk of cancer increases with increasing radiation dose (7), so that the high dose from CT is very concerning (8-14).

There are at least two responses to the high dose and prolific use of CT scanning. The first is to reduce the CT dose to as small as possible (15), and the second is to estimate patient doses accurately and efficiently (16, 17). Many approaches have been developed to reduce the CT patient dose (18). Tube current optimization is the most common. The tube current is proportional to the number of X-ray photons produced and directly proportional to the dose. If the tube current decreases by a half, the dose will be decreased by approximately 50% (19). However, reduction of tube current will result in increased image noise. Consequently, optimization of tube current should be carefully managed, i.e. the tube current should be adjusted to be as small as possible, commensurate with an acceptable noise level. An alternative approach is to use a noise reduction algorithm (20, 21) to reduce the noise, but the spatial resolution is likely to be compromised (21).

A fundamentally different approach is to use dynamic tube current during the scanning process. The tube current is dynamically changed based on the attenuating region: the tube current decreases in low attenuating regions, and increases in high attenuating regions. This technique is called tube current modulation (TCM) (22-24). It allows the user to select a desired noise level or mAs reference. The technique can be used in the axial plane (angular or XY-axis TCM), along the Z-axis (longitudinal TCM), or in a combination of both (25). Using the TCM method the dose can be reduced by 10 - 60% (15).

Another response is to accurately estimate patient dose. Estimating accurate dose is important for evaluating patient cancer-risk and optimization of protocols. The standard descriptor for estimating the output dose of a CT scanner is the volume CT dose index ($CTDI_{vol}$), and the descriptor for estimating individual patient dose is the size-specific dose estimate (SSDE). $CTDI_{vol}$ is measured using a 100 mm pencil ionization chamber and using a standardized PMMA phantom. It is measured in the one axial mode (26, 27), although it has also been validated for estimating the output dose in spiral CT after being corrected for pitch (28, 29). $CTDI_{vol}$ is accepted as an international standard (1, 2, 30-32). The SSDE was established by AAPM report no. 204 in 2011 as a descriptor for estimating patient dose. It is the product of the output dose of the CT scanner ($CTDI_{vol}$) and a conversion factor based on patient size and attenuation.

Up until now, $CTDI_{vol}$ has been calculated using proprietary software, e.g. ImPACT (33) and CT-Expo (34). $CTDI_{vol}$ is calculated based on specific exposure parameters, e.g. tube current, time rotation, pitch, slice width, CT manufacturer, type of scanner and so on. One of the most important exposure parameters is tube current. Because the dynamic tube current is variable in the TCM technique (35), current software is unable to estimate $CTDI_{vol}$ correctly, and cannot estimate patient dose in terms of the size-specific dose estimate (SSDE). The aim of this study is to develop a specific calculator for estimating $CTDI_{vol}$ and SSDE in a CT scanner using the TCM technique. The study also will evaluate the relationships between water equivalent diameter (D_w) and average tube current; between average tube current and $CTDI_{vol}$; and between average tube current and SSDE.

MATERIALS AND METHODS

Patient and CT scanner

We retrospectively studied 57 patients who had undergone CT examinations using the TCM technique. Twenty-seven patients underwent abdominal examination and thirty patients underwent thoracic examination. In the abdominal examination there were 10 female and 17 male patients, and in the thoracic examination there were 14 female and 16 male patients. The age of patients for the abdominal examinations was 48.5 ± 13.9 years, and the age for the thoracic examinations was 55.5 ± 15.9

years. All patients were scanned using a Siemens Somatom Emotion 6 CT scanner. The exposure parameters used are listed in table 1. During the scanning process, the tube current was modulated with a quality reference of mAs (noise level) of 95 mAs for abdominal examinations and 70 mAs for thoracic examinations.

Exposure Parameters	Abdomen Exam	Thorax Exam
Tube current	TCM	TCM
Image quality reference parameter for TCM[a]	95mAs	70mAs
Tube voltage	130kV	130kV
Acquisition detector configuration (N X T)	6x 2.0 mm	6x 2.0 mm
Slice thickness (T)[b]	2mm	2mm
Rotation time	0.6s	0.6s
Pitch	0.8	0.8

aFor Siemens scanners this is known as the Quality reference mAs.
bFor this Siemens scanner this is known as collimated slice width (cSL).

From table 1, the acquisition detector configuration is the product of the number of detector rows (N) and the slice thickness (T). Pitch is the ratio of the table movement per rotation and the detector configuration. The pitch factor can be freely adapted from 0.45 to 2.0. In this study, the pitch was 0.8 for both abdominal and thoracic examinations.

$CTDI_{vol}$ value

We obtained $CTDI_{vol}$ values using two different approaches. In the first approach, $CTDI_{vol}$ values were taken from the CT scanner dose summary as depicted in figure 1. These values were considered reference values. The CT scanner dose summary showed not only the $CTDI_{vol}$ value, but also showed dose length product (DLP), the number of scans (Scan), tube voltage (kV), product of tube current-time (mAs), value of reference tube current for the range (ref), time rotation (TI) and collimated slice thickness (cSL).

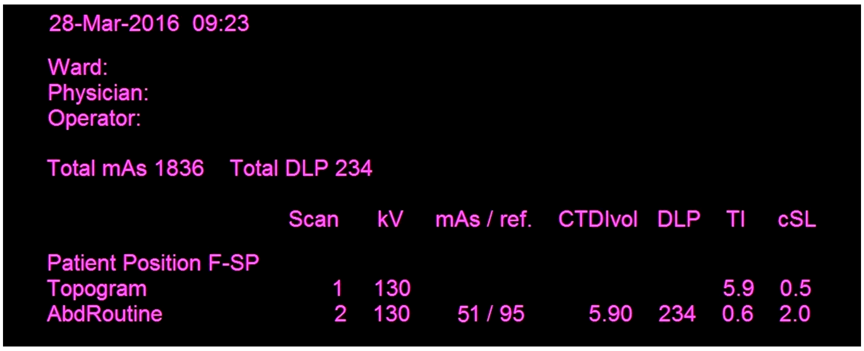

Figure 1. Captured CT dose summary from Siemens Somatom Emotion 6 showing the $CDTI_{vol}$, DLP, mAs, and reference tube current (ref) for the scan range. The rotation time (TI) and collimated slice thickness (cSL) are also shown.

In the second approach, $CTDI_{vol}$ values were calculated from normalized $CTDI_{vol}$ values obtained from proprietary software (ImPACT CT Patient Dosimetry Calculator version 1.0.1a). The unit of normalized $CTDI_{vol}$ is mGy/100 mAs. The normalized $CTDI_{vol}$ is dependent on manufacturer, type of scanner, tube voltage, pitch, collimation width, and so on. If the tube current (mA) and time rotation (s) values are known, then the $CTDI_{vol}$ can be determined.

The $CTDI_{vol}$ value depends on the average tube current (mA). The tube currents in the TCM technique were taken from the DICOM headers and then averaged using equation (1) [35].

$$\overline{\text{mA}} = \sum_{i=1}^{n} \frac{\text{mA}_i}{n} \qquad (1)$$

Figure 2 is a screenshot form for calculating average tube current and $CTDI_{vol}$. The images of all the slices were opened using the TCM button, and all respective tube current values were extracted from the DICOM header and averaged. Figure 2 shows the profile tube current along the longitudinal axis and the average value of tube current (next to TCM button).

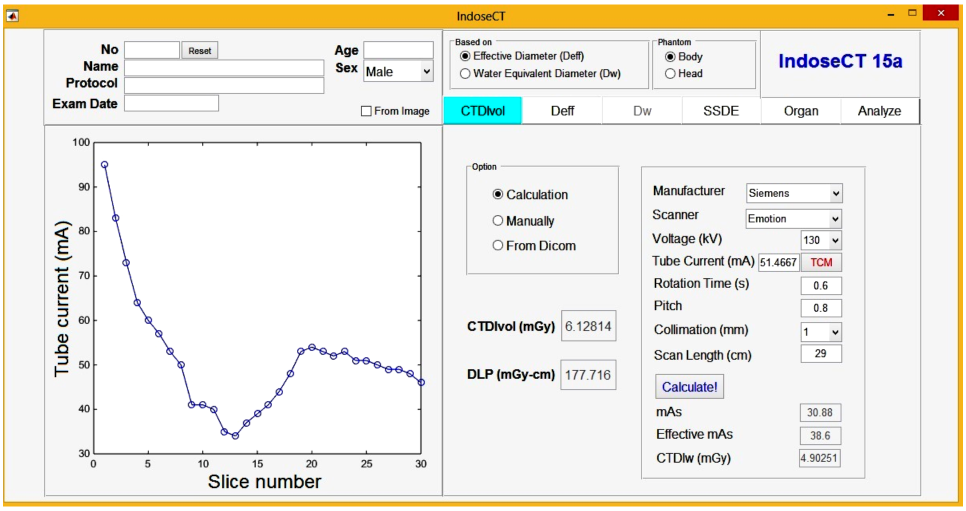

Figure 2. Screenshot form for calculating average tube current and $CTDI_{vol}$.

Water-equivalent diameter (D_w) and size-specific dose estimate (SSDE)

In the TCM technique, the tube current was dynamically changed to fit the attenuating patient expressed in water-equivalent diameter (D_w). The D_w value was calculated for every slice using equation (2):

$$D_W = 2\sqrt{\left[\frac{1}{1000}\overline{\text{HU}} + 1\right]\frac{A}{\pi}} \qquad (2)$$

The average D_w value was estimated using 9 positions, the central slice and 4 slices to the right and left of it. A previous study [17] showed that estimating the average D_w using 9 positions was similar to the average of all slices to within less than 1%. The screenshot form for calculating average D_w is shown in figure 3. It shows the profile D_w along the longitudinal axis at 9 positions. The average D_w value is indicated in red.

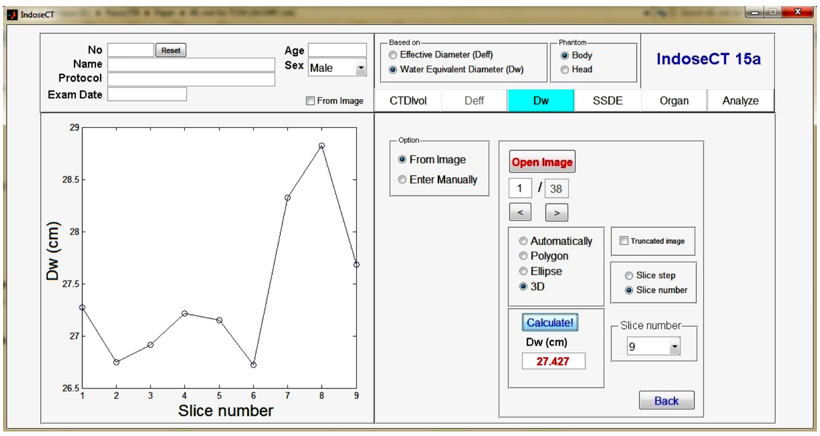

Figure 3. Screenshot form for calculating average D_w. It shows the profile of Dw along the longitudinal axis at 9 positions.

Estimating the dose for a specific patient should take into consideration the $CTDI_{vol}$ and conversion factor as a function of water-equivalent diameter ($k(D_w)$). This conversion factor was taken from AAPM report 204. The equation for estimating SSDE is equation (3).

$$SSDE = CTDI_{vol} \times k(D_w) \quad (3)$$

A screenshot form for calculating SSDE is shown in figure 4. It shows the conversion factor as a function of water-equivalent diameter based on a body PMMA phantom. In this example, D_w was 27.43 cm, $k(D_w)$ was 1.35, $CTDI_{vol}$ was 5.66 mGy, and the estimated SSDE was 7.63 mGy.

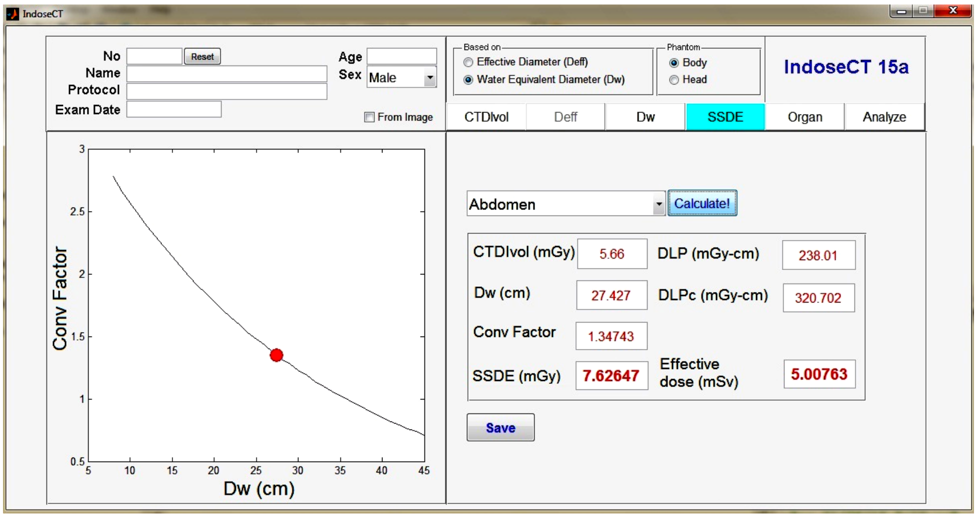

Figure 4. Screenshot form for estimating SSDE.

RESULTS

D_w and tube current

The aim of the TCM technique is to reduce the dose to a small patient. The technique is carried out by reducing tube current in low attenuating regions. The attenuation of the body is characterized by water-equivalent diameter (D_w) which takes into consideration both the size and composition. The relationships between average D_w and average tube current are shown in figure 5. As expected there is a linear correlation between average D_w and average tube current. Values of R^2 were 0.707 and 0.696 for abdominal and thoracic examinations, respectively. The average D_w value for the abdomen was 23.9 ± 1.9 cm, and the average D_w for the thorax was 22.2 ± 2.7 cm. The average tube current for the abdomen was 60.5 ± 12.9 mA, and the average tube current for the thorax was 56.0 ± 16.0 mA.

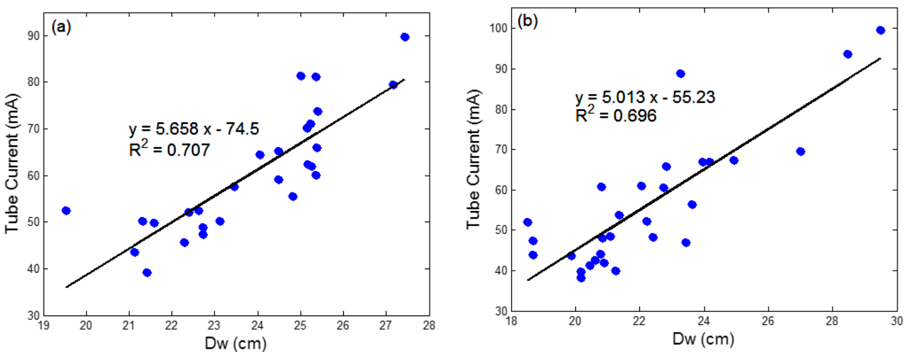

Figure 5. The relationships between average water-equivalent diameter (D_w) and average tube current for (**a**) abdomen and (**b**) thorax.

Tube current and $CTDI_{vol}$

The relationships between average tube current and reported $CTDI_{vol}$ are shown in figure 6. It shows linear correlations between average tube current and $CTDI_{vol}$ with R^2 values of 0.997 and 0.992 for abdominal and thoracic regions, respectively.

Reported and calculated $CTDI_{vol}$

The relationships between reported $CTDI_{vol}$ and calculated $CTDI_{vol}$ are shown in figure 7. It shows linear correlations with R^2 values of 0.997 and 0.992 for abdominal and thoracic regions, respectively. The values of calculated and reported $CTDI_{vol}$ are listed in table 2.

Tube current and SSDE

The relationships between average tube current and SSDE are shown in figure 8. It shows linear correlations between average tube current and SSDE with R^2 values of 0.941 and 0.887 for abdominal and thoracic regions, respectively. The SSDE values were 7.6 ± 1.2 mGy for the abdomen, and 7.3 ± 1.4 mGy for the thorax.

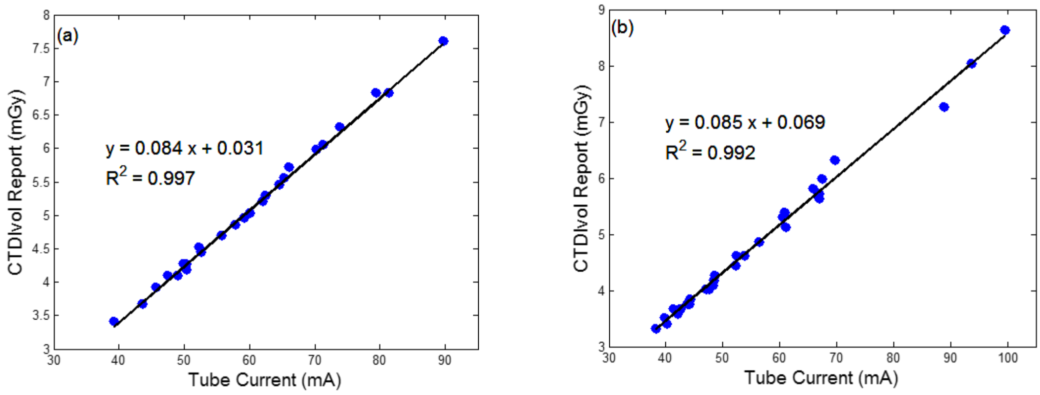

Figure 6. The relationships between average tube current and reported $CTDI_{vol}$ by scanner for (**a**) abdomen and (**b**) thorax.

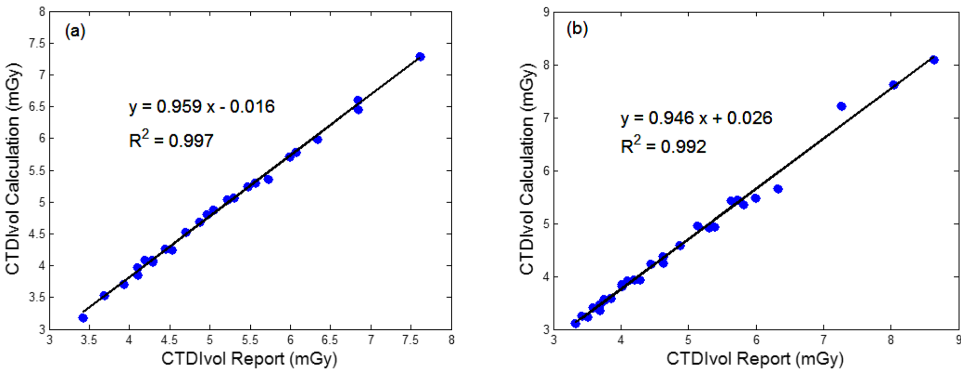

Figure 7. The relationships between reported $CTDI_{vol}$ by scanner and calculated $CTDI_{vol}$ for (**a**) abdomen and (**b**) thorax.

Table 2. The values of calculated and reported CTDIvol for abdominal and thoracic regions

Examination	$CTDI_{vol}$ (mGy)		Percentage Difference (%)
	Report	Calculation	
Abdomen	5.1 ± 1.1	4.9 ± 1.1	4.4 ± 1.2
Thorax	4.8 ± 1.4	4.6 ± 1.3	6.0 ± 2.0

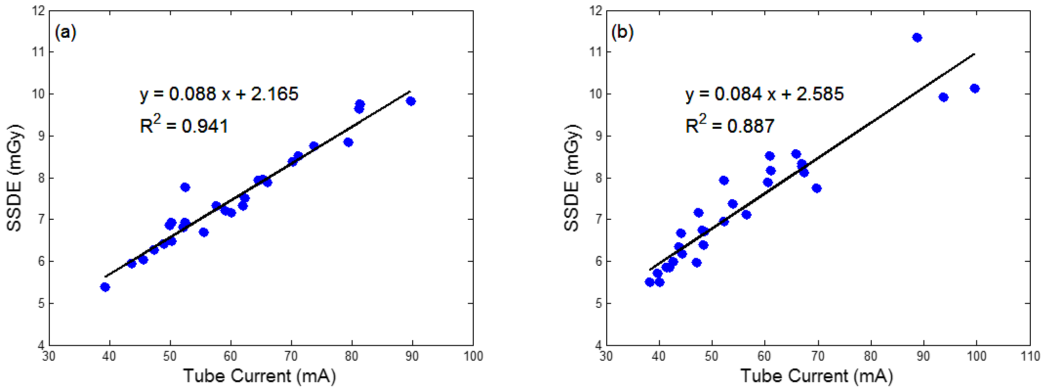

Figure 8. The relationships between average tube current and SSDE for (**a**) abdomen and (**b**) thorax.

DISCUSSION

This study estimates the values of $CTDI_{vol}$ and SSDE in a CT scanner equipped with TCM. To calculate the $CTDI_{vol}$, the exposure parameters, e.g. tube current, should be known. Since the tube current fluctuates during the TCM scanning process, the tube currents were averaged after being extracted from the DICOM headers for every slice. With this approach, it was possible to estimate $CTDI_{vol}$ accurately. The calculated $CTDI_{vol}$ was compared to the $CTDI_{vol}$ reported by the CT scanner. The percentage differences for $CTDI_{vol}$ were 4.4 ± 1.2% and 6.0 ± 2.0% for abdominal and thoracic regions respectively. Our calculated results of $CTDI_{vol}$ are acceptable, since the percentage differences from reported $CTDI_{vol}$ were less than 10%. The calculation of $CTDI_{vol}$ in the TCM technique using ImPACT software and extracting the tube current from the DICOM header had been previously proposed by Lin *et al.* [35]. However they tested the methodology only for the thoracic region of one patient. Their calculated $CTDI_{vol}$ using the ImPACT software was 5.7 mGy and the value reported by the scanner was 5.03 mGy (i.e. a percentage difference of 13.3 %) [35].

In the TCM technique, the tube current dynamically fluctuates based on the attenuating region in terms of the water-equivalent diameter (D_w). This study showed that there is a linear relation between D_w and the average tube current with R^2 values of 0.707 and 0.696 for abdominal and thoracic examinations respectively. Therefore, the average tube current can be estimated by using D_w, and it can be estimated prior to the scanning process. Direct D_w calculation is not trivial. However, it can easily be estimated using the effective diameter (D_{eff}) calculated as the square root of the product lateral diameter (LAT) and the anterior-posterior (AP) diameter [16]. The conversion factors from D_{eff} to D_w are available [12, 36, 37], so that it is possible to estimate the average tube current using D_w and D_{eff} in the TCM technique prior to the scanning process.

By using average tube current, it is also possible to estimate the output CT dose in terms of $CTDI_{vol}$. We have shown that there is a strong linear correlation between the average tube current and $CTDI_{vol}$, with R^2 values of 0.997 and 0.992 for abdominal and thoracic regions, respectively. However, $CTDI_{vol}$ is a metric which measures the output CT scan dose, and it was not intended to measure the dose to the patient. The patient dose should take into consideration both $CTDI_{vol}$ and the attenuation of the patient in terms of water equivalent diameter (D_w). The metric used for estimating the patient dose is size-specific dose estimate (SSDE). It was shown in this study that there is a strong correlation between average tube current and SSDE, with R^2 values of 0.941 and 0.887 for abdominal and thoracic regions respectively.

The relationships between average tube current, $CTDI_{vol}$ and SSDE were interesting. When the tube current varied by a factor of 2.5 the $CTDI_{vol}$ also varied by a factor of 2.5, but the SSDE only varied by a factor of 2 for both abdominal and thoracic regions. Relationships between D_{eff}, $CTDI_{vol}$ and SSDE have also been reported by others[38-40]. Israel *et al.* [38] showed that the exposure varied by a factor of three between individuals who weighed 60 kg and those who weighed 100 kg, and that the dose to the liver varied by a factor of two when TCM (GE Healthcare, Milwaukee, Wis) was used. Schindera *et al.* [39] also showed a similar relationship between radiation exposure and dose with the same scanner. However, Christner *et al* [40] reported that although the exposure was proportional to patient size, SSDE was independent of patient size using TCM with a different scanner (Siemens Healthcare, Forchheim, Germany). Specifically, CTDI$_{vol}$ increased from 12 to 26 mGy as the sum of AP and LAT dimensions increased from 42 to 84 cm. However, this result reflects the different noise level used. Christner *et al* [40] explained that the TCM in their work required lower noise values in children and allowed higher noise values in obese adults compared to adults of standard size. By contrast, the TCM systems used by Israel *et al* [38] and Schindera *et al* [39] produced a constant level of image noise regardless of patient size.

Our study has shown that CTDI$_{vol}$ and SSDE in the TCM technique can be estimated using average tube current extracted from the DICOM headers, and the average tube current can be estimated by the water-equivalent diameter (D$_w$). There are a number of limitations to our study. Firstly, the study is limited to only two anatomic regions, namely the abdomen and thorax. It will be interesting to evaluate the examination of other regions. Secondly, the effect of TCM is affected by noise level (reference mAs) as the results of previous studies [38-40]. Our study is limited to only one reference mAs in the abdominal examination (95 mAs) and one reference value in the thoracic examinations (70 mAs). It will be useful to evaluate the effect of different noise levels (reference mAs) in the future. Thirdly, this study is limited to only one particular scanner.

CONCLUSION

We successfully developed a calculator for estimating CTDI$_{vol}$ and SSDE from a CT scanner equipped with the TCM technique. The calculator used the average tube current from all slices, which is obtained from the DICOM headers. Our study showed that the percentage differences between calculated and reported CTDI$_{vol}$ values were less than 10%. We demonstrated that SSDE can be estimated using average tube current and the water-equivalent diameter (D$_w$).

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Conflicts of interest: *Declared none.*

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