A fully automated calculation of size-specific dose estimates (SSDE) in thoracic and head CT examinations

C Anam¹,², F Haryanto², R Widita², I Arif² and G Dougherty³

¹ Department of Physics, Faculty of Mathematics and Sciences, Diponegoro University, Indonesia
² Department of Physics, Faculty of Mathematics and Natural Science, Institut Teknologi Bandung, Indonesia
³ California State University (CSU) Channel Islands, California, USA

E-mail: anam@fisika.undip.ac.id

Abstract. The purpose of this study is to automatically calculate and then investigate the size-specific dose estimate (SSDE) in thoracic and head CT examinations undertaken using standard imaging protocols. The effective diameter ($D_{\text{eff}}$), the water equivalent diameter ($D_W$), and the SSDE were calculated automatically from patient images. We investigated sixteen adult patients who underwent a CT head examination and thirty adult patients who underwent a CT thorax examination. Our results showed that the $D_W$ value in the thoracic region was 4.5% lower than the value of $D_{\text{eff}}$, while the $D_W$ value in the head region was 8.6% higher than the value of $D_{\text{eff}}$. The relationships between diameter ($D_{\text{eff}}$ and $D_W$) and CTDI$_{\text{vol}}$ were distinctive. In the head region, decreasing the patient diameter resulted in a constant CTDI$_{\text{vol}}$ due to the tube current modulation (TCM) being off, while in the thoracic region decreasing the patient diameter resulted in a decrease in the value of CTDI$_{\text{vol}}$ due to TCM being on. In the head region, decreasing the patient diameter resulted in an increase in the value of SSDE, while in the thoracic region decreasing the patient diameter resulted in a decrease in the value of SSDE.

1. Introduction

The radiation dose from CT examinations is greater than other radiological modalities [1, 2]. Therefore, it is very important to accurately estimate the patient dose and to reduce it to as low as possible. In order to estimate and compare CT radiation doses received by patients, the medical community uses volume CT dose index (CTDI$_{\text{vol}}$) as an indicator [3]. The CTDI$_{\text{vol}}$ is measured using a standard phantom made from polymethylmethacrylate (PMMA) with a diameter of 32 cm to represent the patient’s body and 16 cm to represent the patient’s head and a 100 mm pencil ionization chamber [3]. The CTDI$_{\text{vol}}$ depends on exposure parameters, e.g., tube voltage, tube current, pitch, and so on. However, CTDI$_{\text{vol}}$ is considered to be an output dose indicator only and not a patient dose indicator, because the dose to the patient not only depends on output dose but also depends on the patient’s characteristics [4, 5]. The patient dose indicator which takes into account both output dose and patient characteristics is the size-specific dose estimate (SSDE) [6].

The most obvious patient characteristic is the effective diameter ($D_{\text{eff}}$) [6]. But this alone is not sufficient to determine the patient characteristic because different parts of the patient are composed of different materials [7-9]. Air (lung) is the biggest contributor in the thoracic region, and soft tissue is
the biggest contributor in the abdominal region. Therefore, although the thorax and abdomen may
have the same effective diameter, the dose received by each of them will not be the same. The revised
descriptor for patient characterization is the water equivalent diameter (\(D_W\)) \([7, 10]\).

To reduce the patient dose, new methods and techniques have been introduced, one of which is the
tube current modulation (TCM) technique. TCM changes the tube current continuously to deliver an
approximately constant noise level for the complete scan range \([11]\). In TCM, the user selects a noise
level instead of a tube current value. The scan is started with a pre-selected tube current value which
ensures an adequately recorded signal for the most attenuating region, and then the tube current is
reduced in the regions where the attenuation is lower \([12]\). It was reported that the patient dose was
significantly decreased using TCM compared to non-TCM approaches \([11, 12]\).

This study will automatically calculate effective diameter \((D_{\text{eff}})\), water equivalent diameter \((D_W)\),
and size-specific dose estimate (SSDE). We will investigate the relationship between
\(D_{\text{eff}}\) and \(D_W\) in the thoracic and head examinations. We will also investigate the relationships between patient
diameter \((D_{\text{eff}}\) and \(D_W)\) and dose (CTDI\(_{\text{vol}}\) and SSDE) in the thoracic and head CT examinations using
standard imaging protocols.

2. Method

2.1. The patient images

In this study, we calculated the \(D_{\text{eff}}, D_W\) and SSDE of thirty adult patients who underwent thoracic
examinations and sixteen adult patients who underwent head examinations. The patients were scanned
using a 128-slice multi-detector CT (Aquilion 128, Toshiba, Japan) installed at Kensaras Hospital,
Semarang, Central Java, Indonesia. We used standard protocols both for thoracic and head
examinations. The standard protocol for the thoracic examinations used a voltage of 120 kVp, a pitch
of 1.438, a collimation beamwidth 0.5 mm \(\times\) 64, and 3D tube current modulation. The standard
protocol for the head examinations used a voltage of 120 kVp, a tube current of 300 mA, an exposure
of 225 mAs, a pitch of 0.688, and a collimation beamwidth 0.5 mm \(\times\) 32. The tube current modulation
(TCM) was switched off for the head examinations.

2.2. The automated \(D_{\text{eff}}\) and \(D_W\) calculation

The first step to automate the calculation of \(D_{\text{eff}}\) and \(D_W\) is to contour the patients automatically. The
algorithm used a combination of basic segmentation techniques and specific information about the
border of the patient body \([13]\). The first step was thresholding using a HU value of -200. However,
thresholding alone was not be able to contour the patient accurately because of the presence of objects
inside the patient with HU values lower than -200. To overcome this problem, we used edge detection
to identify these objects and labeled them using their areas. The largest area identified was considered
to be the border of the patient.

After automated contouring, \(D_{\text{eff}}\) and \(D_W\) could be calculated. The calculation of \(D_{\text{eff}}\) was completed
in several steps. The first step was the determination of the center position of the patient. The second
step was the determination of the diameters in the anterior-posterior (AP) and lateral (LAT) directions.
And the final step was the calculation of the effective diameter from the root of the product of the AP
and LAT dimensions.

\[
D_{\text{eff}} = \sqrt{\text{AP} \times \text{LAT}}
\]  

(1)

The calculation of \(D_W\) was also completed in several steps. The results of the automated contouring
were used to crop the original images, and the area of the cropped image and the average HU value of
the patient were calculated. \(D_W\) was then computed using equation (2):

\[
D_W = 2 \sqrt{\frac{1}{1000} \frac{1}{\text{HU} + 1} A}
\]  

(2)
where $A$ is the area of the patient after cropping.

2.3. The SSDE calculation

The values of $\text{CTDI}_{vol}$ were extracted from the DICOM header with the tag [0018, 9345]. The SSDE was calculated by multiplying the value of volume CT dose index ($\text{CTDI}_{vol}$) with the appropriate conversion factors ($f$).

$$\text{SSDE} = \text{CTDI}_{vol} \times f$$  \hspace{1cm} (3)

The conversion factor ($f$) depends on the diameter of the patient ($D_{\text{eff}}$ and $D_W$) based on AAPM report 204 [6]. To calculate the SSDE value for the head, we used the conversion factor from a PMMA phantom 16 cm in diameter, and for the thoracic region, we used a conversion factor from a PMMA phantom 32 cm in diameter.

3. Results

3.1. The relationship between $D_{\text{eff}}$ and $D_W$

The relationship between $D_{\text{eff}}$ and $D_W$ in the thoracic CT examinations is shown in figure 1a. $D_W$ has a strong linear correlation ($R^2 = 0.93$) with $D_{\text{eff}}$. On average the $D_W$ value in the thoracic region is 4.5% smaller than the value of $D_{\text{eff}}$. The relationship between $D_{\text{eff}}$ and $D_W$ in the head CT examinations is shown in figure 1b. $D_W$ is also linearly correlated with $D_{\text{eff}}$, but not as strongly ($R^2 = 0.73$). The $D_W$ value in the head region is on average 8.6% greater than the value of $D_{\text{eff}}$.

![Figure 1](image1.png)

**Figure 1.** (a) The relationships between $D_{\text{eff}}$ and $D_W$ for the thoracic examinations, (b) for the head examinations.

3.2. Relationship between diameter ($D_{\text{eff}}$ and $D_W$) and dose ($\text{CTDI}_{vol}$ and SSDE)

The relationship between $D_{\text{eff}}$ and dose ($\text{CTDI}_{vol}$ and SSDE) for the thoracic examinations are shown in figure 2a, and the relationships between $D_W$ and dose ($\text{CTDI}_{vol}$ and SSDE) are shown in figure 2b. Figure 2a shows that the value of $\text{CTDI}_{vol}$ increases with increasing diameters ($D_{\text{eff}}$ and $D_W$). The increased $\text{CTDI}_{vol}$ leads to an increase in SSDE. From figures 2a and 2b, it seems that the correlation between diameters ($D_{\text{eff}}$ and $D_W$) and $\text{CTDI}_{vol}$ is stronger (with $R^2$ about 0.8) than the correlation between diameters ($D_{\text{eff}}$ and $D_W$) and SSDE (with $R^2$ about 0.5). This is due to the calculation of $\text{CTDI}_{vol}$ being directly based on the average mAs which fluctuates along the z-axis in the TCM mode. Thus, the correlation between diameters ($D_{\text{eff}}$ and $D_W$) and $\text{CTDI}_{vol}$ is strong. $\text{CTDI}_{vol}$ was converted into SSDE using a conversion factor ($f$), which reduced the correlation between diameters and SSDE in the TCM mode.
From figures 2a and 2b, SSDE seems to be highest at 24 cm then drops when the diameters ($D_{eff}$ and $D_w$) increase. This is most likely due to the exponential nature of the conversion factor ($f$), whose value decreases with increasing diameters ($D_{eff}$ and $D_w$).

The relationships between $D_{eff}$ and dose (CTDIvol and SSDE) for the head examinations are shown in figure 3a, and the relationships between $D_w$ and dose (CTDIvol and SSDE) are shown in figure 3b. The value of CTDIvol is constant with increasing diameters ($D_{eff}$ and $D_w$). The constant value of CTDIvol and the increasing diameters (resulting in decreasing $f$ values) make the value of SSDE decrease. Figure 3a shows a cross-over value of $D_{eff}$ between 16 and 16.5 cm. When $D_{eff}$ is smaller than the cross-over value the SSDE value is greater than CTDIvol, and vice versa. On the other hand, all the SSDE values based on $D_w$ are smaller than the CTDIvol values.

Figure 2. (a) Relationship between $D_{eff}$ and SSDE; $D_{eff}$ and CTDIvol, (b) $D_w$ and SSDE; and $D_w$ and CTDIvol for the thoracic examinations.

Figure 3. (a) Relationship between $D_{eff}$ and SSDE; and $D_{eff}$ and CTDIvol, (b) $D_w$ and SSDE; and $D_w$ and CTDIvol for the head examinations.

4. Discussion
We have developed software for the automated estimation of $D_{eff}$, $D_w$, and SSDE. The software works without any user intervention.

Figure 1a shows that in thoracic examinations, the value of $D_w$ is smaller than $D_{eff}$. This is due to the presence of the lung in the thorax. The HU value for air in the lung is approximately -1000. The presence of air in the lung makes the value of $D_w$ smaller, whereas the value of $D_{eff}$ is calculated only from the effective diameter and it is assumed that the patient composition is close to water with an HU value around 0. On the other hand, figure 1b shows that in head examinations, the value of $D_w$ is...
greater than $D_{\text{eff}}$. This is because the biggest contributors to the head are soft tissue with HU value around 0 and bone with HU value around 1000+.

Since $D_W$ considers not only the diameter of the patient, but also the composition of the patient, $D_W$ is considered to be more appropriate than $D_{\text{eff}}$. However, the calculation of $D_W$ is more difficult than $D_{\text{eff}}$. In practice, the value of $D_W$ can be estimated from $D_{\text{eff}}$ using equation 4 and 5 for thoracic and head examinations, respectively.

$$D_W = 0.994 \times D_{\text{eff}} - 31.014 \quad (4)$$

$$D_W = 0.882 \times D_{\text{eff}} + 3.424 \quad (5)$$

The relationships between patient diameters ($D_{\text{eff}}$ and $D_W$) and CTDI$_{\text{vol}}$ are very interesting. Figure 2a shows that CTDI$_{\text{vol}}$ increases with increasing $D_{\text{eff}}$. This reflects the effect of TCM. In the TCM technique, if the diameter decreases, the tube current will proportionally decrease and this will reduce CTDI$_{\text{vol}}$. In contrast, with a non-TCM technique CTDI$_{\text{vol}}$ is constant with decreasing or increasing diameters ($D_{\text{eff}}$ and $D_W$) because the tube current is constant and independent of the diameter of the patient.

For the head examinations, figure 3a shows that although CTDI$_{\text{vol}}$ is constant with increasing $D_{\text{eff}}$, SSDE decreases with increasing $D_{\text{eff}}$. We know from the AAPM table, the conversion factor ($f$) decreases with an increase of $D_{\text{eff}}$, therefore SSDE will decrease with an increase of $D_{\text{eff}}$ in the case of a constant CTDI$_{\text{vol}}$ value. The cross-over value at $D_{\text{eff}}$ between 16 and 16.5 cm is based on the AAPM conversion factor ($f$). Figure 3b shows that all SSDE values are lower than CTDI$_{\text{vol}}$ values.

Figure 3a and 3b show that the CTDI$_{\text{vol}}$ is constant with either decreasing or increasing diameter ($D_{\text{eff}}$ and $D_W$). This is because TCM was not activated in the standard protocol for adult head examinations. Activating TCM in a head examination would not result in a high variation of dose due to the small variation in head diameter for our patients ($D_{\text{eff}}$ between 15.96 and 17.60 cm, and $D_W$ between 17.21 and 18.97 cm). However, activating TCM for the standard head protocol will decrease the dose (SSDE), and thus improve patient safety.

5. Conclusions
We have proposed an algorithm for the automated calculation of $D_{\text{eff}}$, $D_W$, and SSDE. We conclude that for thoracic examinations, the radiation dose (SSDE) decreases with a decrease in patient diameter when TCM is activated. For examinations of the head, the radiation dose (SSDE) increases with a decrease in patient diameter, if TCM is not activated.

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