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The Evaluation of the Effective Diameter (D_{eff}) Calculation and its Impact on the Size-Specific Dose Estimate (*SSDE*)

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ABSTRACT

Information on the effective diameter (D_{eff}) is essential for estimating the dose for patients undergoing CT examinations. The purpose of this study was to calculate the effective diameter using the maximum values of lateral (LAT) and anterior-posterior (AP) diameters ($D_{eff,m}$) and using LAT and AP diameters taken from the center of the image ($D_{eff,c}$), and compare both estimates to the effective diameter calculated directly from the cross-sectional area of the patient ($D_{eff,A}$). We evaluated 164 patients who underwent the four most frequent CT examinations, namely pelvic, abdominal, thoracic, and head examinations, using a multi-detector CT (MDCT), the Toshiba Aquilion 128. We used the Wilcoxon-Mann-Witney *U* test to statistically determine whether differences were significant. While $D_{eff,m}$ is statistically no different ($p > 0.05$) from $D_{eff,A}$, $D_{eff,c}$ is statistically different ($p < 0.05$) from $D_{eff,A}$ except for head examinations.

INTRODUCTION

Computed tomography (CT) is a remarkable imaging modality which produces high-quality 3D images with fast acquisition times. The CT scan is becoming an increasingly popular and effective diagnostic tool. Therefore, CT is considered as the gold standard in medical imaging.

However, CT delivers a higher radiation dose to the patient than other imaging modalities, and consequently also poses a higher risk of cancer [1]. The American Association of Physicists in Medicine (AAPM) reported in 2008 [2] that the effective doses of head CT, chest CT, abdominal CT, pelvic CT, abdominal-pelvic CT, coronary artery calcium CT, and coronary CT angiography examinations were 1-2, 5-7, 5-7, 3-4, 8-14, 1-3, and 5-15 mSv, respectively. By comparison, the effective doses of dental bitewing, chest radiograph, lumbar spine radiograph, mammogram, barium enema exam, and coronary angiogram were <0.1, 0.1-0.2, 0.5-1.5, 0.3-0.6, 3-6, 5-10 mSv, respectively.

The radiation dose associated with a CT scan is in the range of 1-15 mSv. The effective dose in this range is comparable to the annual dose received from natural radiation sources such as radon and cosmic radiations (1-10 mSv) [3].

Estimates of the risk of cancer from exposure to ionizing radiation, including CT scans, comes from epidemiological studies of the survivors of the 1945 atomic bombings in Japan [4]. However, recently, several epidemiologic studies for estimating cancer from CT examinations have been reported [5,6]. Several studies have shown that, the risk of cancer is known to increase with increasing radiation dose [4-6]. Therefore, the relatively high CT dose should be reduced.

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The CT dose needs to be estimated in order to optimize scanning protocols. The estimation and evaluation of radiation dose to the patient have relied on the output of the CT scanner, in terms of volume CT dose index ($CTDI_{vol}$) and the dose-length product (DLP). The output of CT scanner is determined for standard-sized cylindrical phantoms (either 16 cm or 32 cm diameter) and their conversion factor to effective dose derived for patients of typical size [7]. As such, the dose to individual patients is not available.

Patient size is strongly correlated to the dose received, and hence to the individual's radiation risk. For constant exposure factors (such as tube voltage, tube current, pitch, and beam width), it had been reported by many authors that if the size of the patient decreases, the radiation dose increases [8,9]. The American Association of Physicists in Medicine (AAPM) [10] in 2011 issued a report estimating patient-specific dose in terms of size-specific dose estimate (*SSDE*) and emphasizing that the effective diameter of patient (D_{eff}) and the volume CT dose index ($CTDI_{vol}$) should be taken into consideration. For more accurate estimation, the patient-specific dose should take into consideration not only the effective diameter, but also the attenuation (composition) of each patient in terms of water equivalent diameter (D_w) [11-14]. Several studies estimated D_w from D_{eff} [14-16], underscoring the necessity of an accurate D_{eff} calculation.

The effective diameter can be estimated prior to the CT examination using a scanned projection radiograph (SPR) image or it can be calculated afterwards using an axial CT image. Pourjabbar *et al.* [17] reported that the estimate of D_{eff} using an axial image provides less variability than using an SPR image. They calculated the effective diameter as the root of the product of lateral (LAT) and anterior-posterior (AP) diameters [10,17]. Usually, LAT and AP diameters are chosen in a position that gives maximum values [10,18]. Other studies [15,19] estimated the D_{eff} in the axial image, using LAT and AP diameters from the center of the image. In fact, the maximum values of LAT and AP diameters only occur in the center of the image if the geometry of the patient has a circular or elliptical cross-section, which is not the case for most real patients. We calculated the effective diameter using both the maximum diameters ($D_{eff,m}$) [10] and the central LAT and AP diameters ($D_{eff,c}$) [19], and compared both estimates to the effective diameter calculated directly from the patient cross-section ($D_{eff,A}$). We focused on the four most frequent CT examinations, namely the examinations of the pelvis, abdomen, thorax, and head.

EXPERIMENTAL METHODS

The images of patients

We evaluated 164 patients who underwent various CT examinations at Kensaras Hospital, Semarang, Central Java, Indonesia, using a multi-detector CT (MDCT) scanner, the Toshiba Aquilion 128. The details of the patients and examinations are listed in Table 1.

Table 1. The details of the the patients and examinations

	Pelvis	Abdomen	Thorax	Head
Number of patients	41	48	58	17
Age				
Mean (y)	56.8	47.7	49.1	44.2
Std Deviation (y)	11.7	12.7	10.1	15.2
Min (y)	32	15	28	13
Max (y)	82	74	77	72
Sex				
Male	11	8	3	8
Female	30	40	55	9
Tube Voltage (kVp)	120	120	120	120
Tube Current (mA)	TCM*	TCM*	TCM*	300
Time rotation (ms)	500	500	500	750
Pitch	0.938	1.438	1.438	0.688
Slice thickness (mm)	2	2	2	2

*Tube Current Modulation

The D_{eff} calculation

The effective diameter was directly calculated from the cross-sectional area of the patient (*A*):

$$D_{eff,A} = 2\sqrt{\frac{A}{\pi}} \quad (1)$$

The effective diameter was also estimated from the magnitude of diameter in the lateral (LAT) and anterior-posterior (AP) directions [10]:

$$D_{eff} = \sqrt{\mathrm{AP}\, x\, \mathrm{LAT}} \quad (2)$$

Equation (2) assumes that the patient's cross section is either circular or elliptical. Deciding the best values of LAT and AP diameter is tricky. The maximum values occur in the central image only for circular and elliptical geometry. However, real patients' geometries are neither fully circular nor elliptical in cross section. Many investigators follow AAPM (2011) and use the maximum diameters, in whichever slice they occur, to estimate the effective diameter ($D_{eff,m}$) and the size-specific dose estimate ($SSDE_m$) [10,18]. Anam *et al*. [19] developed software to automatically calculate the D_{eff} using diameters from the central image to estimate effective diameter ($D_{eff,c}$) and size-specific

dose estimate ($SSDE_c$). This study will investigate the differences, if any, in using $D_{eff,c}$ and $D_{eff,m}$ and compare them to $D_{eff,A}$, the value measured directly from the cross-sectional area.

In this study, we only evaluated the center image (slice) of the 3D image stacks of the patients. A typical image is shown in Fig. 1 (a). We used the automated patient contouring proposed by Anam *et al*. [19]. The result is shown in Fig. 1 (b). We then calculated the area of the patient and calculated the effective diameter based on the real area ($D_{eff,A}$) using equation (1). Afterward, we automatically calculated the diameters of the patient in the LAT and AP directions from the central image and calculated the effective diameter based on these two diameters ($D_{eff,c}$) using equation (2). The position of these diameter measurements is shown in Fig. 1 (c). Finally, we automatically calculated the maximum diameters of the patient in LAT and AP positions from the image and calculated the effective diameter based on these two diameters ($D_{eff,m}$) using equation (2). The position of these diameter measurements is shown in Fig. 1 (d).

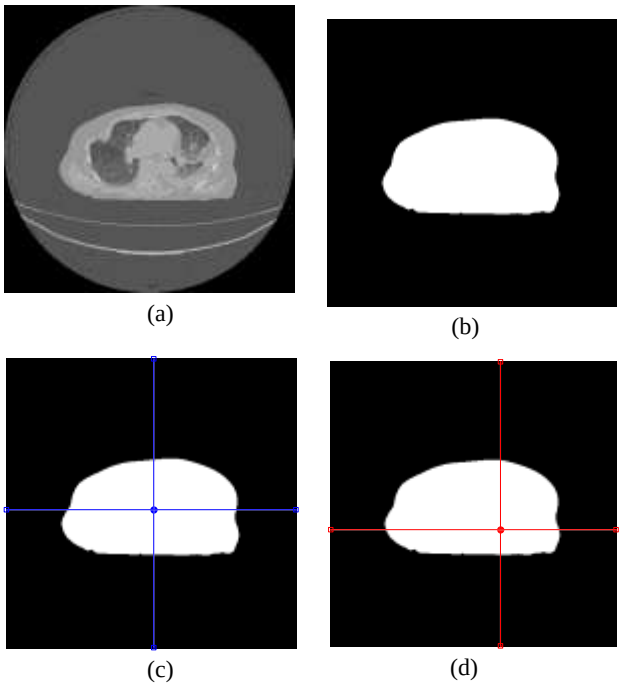

Fig. 1. (a) Example of patient image, (b) Result of auto-contouring to directly determine the effective diameter ($D_{eff,A}$), (c) The central position of LAT and AP diameters, to estimate central effective diameter ($D_{eff,c}$), (d) The maximum LAT and AP diameters, to estimate maximum effective diameter ($D_{eff,m}$).

The *SSDE* calculation

From the three effective diameters, namely $D_{eff,A}$, $D_{eff,c}$, and $D_{eff,m}$, we computed three size-specific dose estimates (*SSDE*s), namely $SSDE_A$, $SSDE_c$, and $SSDE_m$, using equation (3).

$$SSDE = CTDI_{vol} \times f(D_{eff}) \quad (3)$$

The $CTDI_{vol}$ value reflects the output dose of a CT scanner and it is determined by many factors, such as tube voltage, tube current, pitch, beam width, and type of filter. In this study, we extracted the $CTDI_{vol}$ value from the DICOM header of each patient's image. The conversion factor, $f(D_{eff})$, from $CTDI_{vol}$ to *SSDE* depends on two parameters, namely D_{eff} and the type of phantom used, whether head or body phantom. To calculate the *SSDE* for the head examination, $f(D_{eff})$ was taken from table 2 D, and to calculate the *SSDE* for pelvis, abdomen, and thorax, it was taken from table 1 D of AAPM report 204 [10].

Statistical analysis

The relationship between $D_{eff,m}$ and $CTDI_{vol}$ was analyzed using linear regression. We compared $D_{eff,c}$ with $D_{eff,A,}$ and also $D_{eff,m}$ with $D_{eff,A}$. We calculated their average, deviation standard, minimum value and maximum value of percentage differences. We also performed a statistical test using the Wilcoxon-Mann-Witney *U* test. A *p* value of less than 0.05 was considered to indicate a statistically significant difference.

RESULTS AND DISCUSSION

The relationship between $D_{eff,m}$ and $CTDI_{vol}$

The relationship between $D_{eff,m}$ and $CTDI_{vol}$ for pelvic, abdomi,al thoracic, and head examinations are indicated in Fig. 2. It can be seen that in the head examination, the $CTDI_{vol}$ values were constant with changing $D_{eff,m}$ values. On the other hand, in the pelvic, abdominal, and thoracic examinations, the $CTDI_{vol}$ increases with increasing of $D_{eff,m}$ values. The R^2 values for the pelvic, abdominal, and thoracic examinations were 0.711, 0.670, and 0.655, respectively. The increase of $CTDI_{vol}$ with the increasing $D_{eff,m}$ values indicates the tube current modulation (TCM) function that has been activated in these examinations (Table 1). The main goal of activating TCM is to reduce the patient dose in small patients, especially in the pediatric patients.

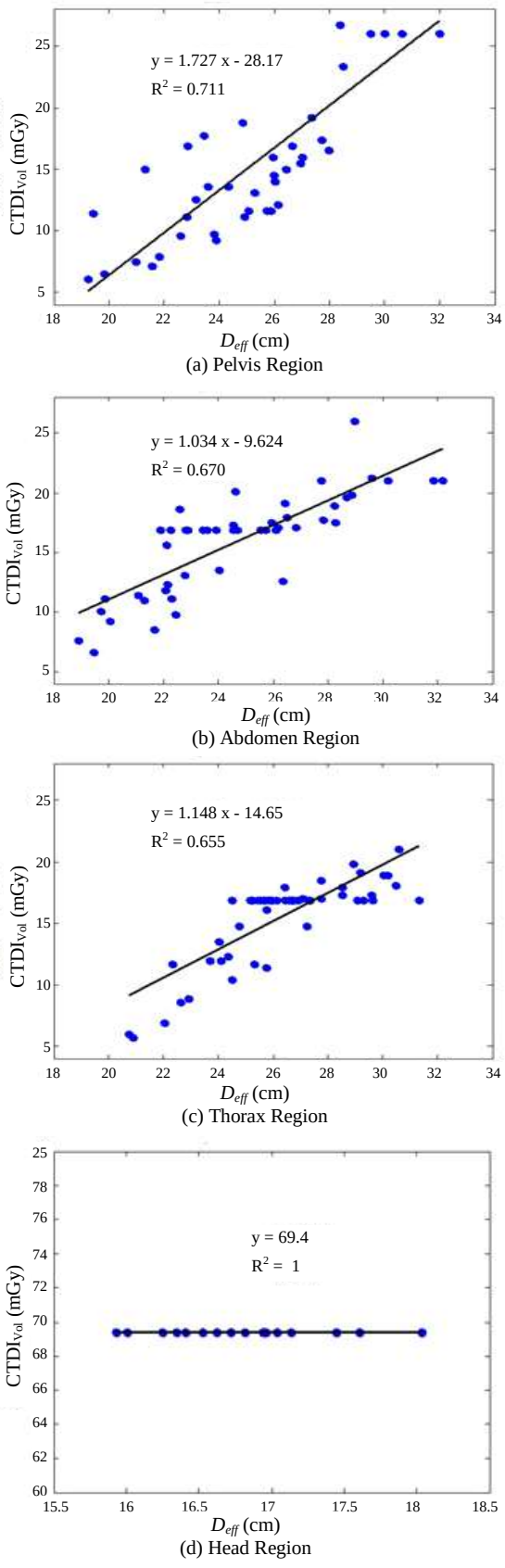

Fig. 2. The relationship between $D_{eff,m}$ and $CTDI_{vol}$ for pelvis (a), abdomen (b), thorax (c), and head examinations (d).

The average and standard deviation of $D_{eff,m}$ values are listed in Table 2. The $D_{eff,m}$ values are 26.1 ± 3.0 cm, 25.5 ± 3.4 cm, 26.9 ± 2.4 cm, and 16.8 ± 0.6 cm for pelvic, abdominal, thoracic, and head examinations, respectively. It is clear that head $D_{eff,m}$ has a small standard deviation (< 1 cm). Therefore, TCM is not activated for this head standard examination. It differs from other parts of body (pelvis, abdomen, and thorax) for which the standard deviations are relatively high (> 2 cm). Therefore, to reduce dose in the small size of patient, the TCM is activated in these standard examinations. A previous study [20] reported that TCM is used routinely for chest, abdominal, and pelvic CT examinations, but is often not used routinely for head CT exams. However, the use of TCM for head examinations has the potential to reduce CT dose [20].

Table 2. The $D_{eff,c}$, $D_{eff,m}$ and $D_{eff,A}$ values, percentage differences between $D_{eff,c}$ and $D_{eff,A}$, and percentage differences between $D_{eff,m}$ and $D_{eff,A}$

	Pelvis	Abdomen	Thorax	Head
$D_{eff,A}$ (cm)				
Mean	26.09	25.53	26.89	16.83
Std Deviation	3.01	3.39	2.35	0.58
Min	19.38	19.71	21.08	15.61
Max	31.71	33.21	31.78	17.87
$D_{eff,c}$ (cm)				
Mean	24.08	24.08	25.41	16.46
Std Deviation	2.97	3.33	2.16	0.56
Min	18.82	18.53	20.06	15.16
Max	30.84	31.97	29.60	17.47
$D_{eff,m}$ (cm)				
Mean	25.35	24.70	26.36	16.81
Std Deviation	3.17	3.28	2.37	0.56
Min	19.25	18.91	20.76	15.93
Max	31.98	32.19	31.32	18.04
Percentage difference $D_{eff,c}$ and $D_{eff,A}$ (%)				
Mean	5.44	5.73	5.46	2.19
Std Deviation	1.72	1.48	1.82	0.73
Min	0.60	2.45	1.75	0.95
Max	8.74	9.02	10.42	3.79
p value	0.04	0.04	< 0.01	0.09
Percentage difference $D_{eff,m}$ and $D_{eff,A}$ (%)				
Mean	2.92	3.24	1.99	0.12
Std Deviation	2.09	1.00	1.39	1.69
Min	-2.99	0.78	-2.47	-5.01
Max	6.82	5.57	5.65	1.77
p value	0.29	0.19	0.12	0.86

The relationships between $D_{eff,c}$, $D_{eff,m}$, and $D_{eff,A}$

The $D_{eff,c}$, $D_{eff,m}$, and $D_{eff,A}$ values, percentage differences between $D_{eff,c}$ and $D_{eff,A}$, and percentage differences between $D_{eff,m}$ and $D_{eff,A}$ are listed in Table 2. As predicted, all $D_{eff,m}$ values are lower than the corresponding $D_{eff,A}$ values, and all $D_{eff,c}$ values are lower than the corresponding $D_{eff,m}$ values. This confirms that geometry of pelvic, abdominal,

thoracic, and head patients were not completely circular or elliptical. The head is nearest to being circular or elliptical, while the abdomen is the farthest from a circular or elliptical shape.

The *p* values between $D_{eff,m}$ and $D_{eff,A}$ for all examinations (pelvis, abdomen, thorax, and head) are > 0.05, indicating no significant difference between $D_{eff,m}$ and $D_{eff,A}$ for all examinations. However, the *p* values (< 0.05) between $D_{eff,c}$ and $D_{eff,A}$ point out a statistical difference in shape, except for the head examination.

The relationships between $SSDE_c$, $SSDE_m$, and $SSDE_A$

The $SSDE_c$, $SSDE_m$, and $SSDE_A$ values, percentage differences between $SSDE_c$ and SSDE_A, and percentage differences between $SSDE_m$ and $SSDE_A$ are listed in Table 3. All $SSDE_m$ values are higher than the corresponding $SSDE_A$ values, because all $D_{eff,m}$ values are lower than $D_{eff,A}$ values. Also, all $SSDE_c$ values are higher than the corresponding $SSDE_m$ values, because all $D_{eff,c}$ values are also smaller than $D_{eff,m}$ values.

Table 3. The $SSDE_c$, $SSDE_m$ and $SSDE_A$ values, percentage differences between $SSDE_c$ and $SSDE_A$, and percentage differences between $SSDE_m$ and $SSDE_A$

	Pelvis	Abdomen	Thorax	Head
$SSDE_A$ (mGy)				
Mean	21.48	22.65	21.26	67.78
Std Deviation	6.95	4.30	3.67	1.63
Min	10.85	11.73	9.50	64.86
Max	36.39	31.95	25.11	71.17
$SSDE_c$ (mGy)				
Mean	22.62	23.92	22.47	68.81
Std Deviation	7.32	4.68	3.90	1.56
Min	11.17	12.13	10.03	65.96
Max	37.83	33.96	26.87	72.43
$SSDE_m$ (mGy)				
Mean	22.04	23.37	21.72	67.85
Std Deviation	7.03	4.50	3.83	1.55
Min	11.13	11.96	9.79	64.46
Max	36.92	33.31	25.41	70.29
Percentage difference $SSDE_c$ and $SSDE_A$ (%)				
Mean	5.31	5.45	5.68	1.53
Std Deviation	1.60	1.41	2.24	0.53
Min	0.38	2.02	1.75	0.62
Max	7.70	8.70	12.72	2.75
p value	0.42	0.06	< 0.01	0.09
Percentage difference $SSDE_m$ and $SSDE_A$ (%)				
Mean	2.75	3.12	2.08	0.11
Std Deviation	1.89	1.06	1.56	1.15
Min	-2.53	0.64	-2.53	-3.44
Max	6.40	5.68	6.47	1.30
p value	0.61	0.23	0.10	0.86

The data indicates that the lowest percentage difference between $SSDE_{,m}$ and $SSDE_A$, and between $SSDE_c$ and $SSDE_A$, is in the head examination and the highest is in abdominal examination. All the *p* values between $SSDE_{,m}$ and $SSDE_A$ for all examinations (pelvic, abdominal, thoracic, and head) are > 0.05. Also, all the *p* values between $SSDE_c$ and $SSDE_{A,}$ except for thoracic examinations are > 0.05.

An accurate calculation of D_{eff} and *SSDE* should use the actual cross-sectional area of the patient. However, this calculation is time consuming. For a more practical approach, $D_{eff,m}$ and $D_{eff,c}$ can be used instead. The aim of this study was to evaluate $D_{eff,m}$ and $D_{eff,c}$ and their impact to the size-specific dose estimate values in the most common examinations, namely pelvic, abdominal, thoracic, and head examinations. Previous studies had either used $D_{eff,m}$ [18] or $D_{eff,c}$ [15,19] to calculate *SSDE*.

The main finding of our study is that the effective diameter can be accurately estimated from the square root of the product of the maximum LAT and AP diameters. This effective diameter ($D_{eff,m}$) as used by AAPM 204 [10] and other investigators [18] is statistically no different ($p > 0.05$) from the effective diameter calculated using the actual cross-sectional area of the patient ($D_{eff,A}$). The percentage differences between them are 2.9 %, 3.2 %, 2.0 % and 0.1 % for pelvic, abdominal, thoracic, and head examinations, respectively. Also, $SSDE_m$ is not statistically different ($p > 0.05$) from $SSDE_A$.

The effective diameter should not be estimated using the LAT and AP diameters from the central slice as used by Ikuta *et al.* [15] and Anam *et al.* [19], except for head examination. These effective diameters ($D_{eff,c}$) are statistically different ($p < 0.05$) from effective diameters calculated using the actual area of the patient ($D_{eff,A}$), except for head examinations. The percentage differences between them are 5.4 %, 5.7 %, 5.5 %, and 2.2 % for pelvic, abdominal, thoracic, and head examinations, respectively. However, if they are used, a conversion factor from $D_{eff,c}$ to $D_{eff,A}$ should be implemented.

The estimation of effective diameter is essential for an accurate estimation of *SSDE*, although the use of only patient size (i.e. effective diameter) is not enough to predict the *SSDE*. The more appropriate metric is water equivalent diameter (D_w) which combines the patient size and attenuation (composition) of patients [12,13]. This would require a further study to convert D_{eff} to D_w for every body part of a CT examination.

CONCLUSION

We have investigated $D_{eff,m}$ and $D_{eff,c}$ for pelvic, abdominal, thoracic, and head examinations. $D_{eff,m}$ is statistically no different ($p > 0.05$) from $D_{eff,A}$. On the other hand, $D_{eff,c}$ is statistically different ($p < 0.05$) from $D_{eff,A}$, except for head examinations. The size-specific dose estimate, $SSDE_m$ and $SSDE_c$ are statistically no different ($p > 0.05$) from $SSDE_A$, except for thoracic examinations, for which $SSDE_c$ is statistically different from $SSDE_A$.

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