Scientific Paper

The effective and water-equivalent diameters as geometrical size functions for estimating CT dose in the thoracic, abdominal, and pelvic regions

Winda Kusuma DEWI¹, Choirul ANAM¹, Eko HIDAYANTO¹, Arrum NITASARI¹, Geoff DOUGHERTY²

¹Department of Physics, Faculty of Sciences and Mathematics, Diponegoro University, Jl. Prof. Soedarto SH, Tembalang, Semarang 50275, Central Java, Indonesia.

²Department of Applied Physics and Medical Imaging, California State University Channel Islands, Camarillo, CA 93012, USA

*E-mail address: anam@fisika.fsm.undip.ac.id

Abstract

Purpose: The aim of this work was to establish the relationships of patient size in terms of effective diameter (D_{eff}) and water-equivalent diameter (D_w) with lateral (LAT) and anterior-posterior (AP) dimensions in order to predict the specific patient dose for thoracic, abdominal, and pelvic computed tomography (CT) examinations.

Methods: A total of 47 thoracic images, 79 abdominal images, and 50 pelvic images were analyzed in this study. The patient's images were retrospectively collected from Dr. Kariadi and Kensas Hospitals, Semarang, Indonesia. The slices measured were taken from the middle of the scan range. The calculations of patient sizes (LAT, AP, D_{eff} , and D_w) were automatically performed by IndoseCT 20b software. D_{eff} and D_w were plotted as functions of LAT, AP, and AP+LAT. In addition, D_w was plotted as a function of D_{eff} .

Results: Strong correlations of D_{eff} and D_w with LAT, AP, and AP+LAT were found. Stronger correlations were found in the D_{eff} curves ($R^2 > 0.9$) than in the D_w curves ($R^2 > 0.8$). It was found that the average D_{eff} was higher than the average D_w in the thoracic region, the average values were similar in the abdominal and pelvic regions.

Conclusion: The current study extended the study of the relationships between D_{eff} and D_w and the basic geometric diameter LAT, AP, and AP+LAT beyond those previously reported by AAPM. We evaluated the relationships for three regions, i.e. thoracic, abdominal, and pelvic regions. Based on our findings, it was possible to estimate D_{eff} and D_w from only the LAT or AP dimension.

Key words: anterior-posterior dimension; lateral dimension; effective diameter; water-equivalent diameter; computed tomography.

Introduction

The capability of computed tomography (CT) to produce high-quality images has steadily grown since its introduction in the 1970s. Improvements in CT hardware has led to a new generation of multidetector-row CT (MDCT) with greater X-ray tube power, faster acquisition time, and dual-energy and even multi-energy x-rays capabilities.^{1,2} Currently, one axial image can be acquired in 0.005 seconds, whereas it took about 300 seconds to acquire one axial image in a first-generation scanner.³ Advances in software have led to iterative reconstruction (IR) techniques and tube current modulation (TCM) allowing low dose CT.^{2,4} These improvements have made CT a reliable and desirable imaging modality. In cardio-thoracic imaging, for example, MDCT has become a viable non-invasive option due to its ability to accurately evaluate coronary artery abnormalities.⁵

An annual statistical study by National Health Service (NHS), England, reported that 5,959,860 examinations used CT scanners in 2019/2020.⁶ This number has increased by 5.2% compared to the previous year and it was predicted that it will continue to increase for the next few years. This trend of increasing use of CT also occurred in North America, Asia, and Italy.^{7,8} As a consequence these populations will receive high x-ray doses.⁹

There have been several indicators used to quantify dose radiation of CT scanners, such as multiple scan average dose (MSAD), computed tomography dose index (CTDI) and its derivatives, dose length product (DLP), and effective dose.¹⁰ Volume computed tomography dose index (CTDI_{vol}) is the most widely used indicator now. It is affected by the input scanning parameters such as tube voltage, tube current, rotation time, pitch, and beamwidth.^{11,12} However, it really only monitors scanner radiation output; it is independent of patient size, and

thus, it does not indicate the radiation received by the patient's body. It is well-known that an accurate metric of the patient dose is not only affected by the scanning parameters, but by the patient's size and attenuation.¹³ A more appropriate metric corresponding to the patient geometrical size is the size-specific dose estimate (SSDE), introduced by the American Association of Physicists in Medicine (AAPM) in Report No 204.¹⁴

A specific geometrical size factor was used to normalize $CTDI_{vol}$ to obtain the SSDE value. The fundamental geometrical sizes are anterior-posterior (AP) and lateral (LAT) dimensions, and an advanced geometrical size is an effective diameter (D_{eff}), which can be calculated from AP and LAT dimensions. An approximation to D_{eff} using AP or LAT is very helpful for the busy clinical center. This approximation is based on the relationship between AP and D_{eff} , or LAT and D_{eff} .

Unfortunately, the geometrical size given in AAPM Report No. 204 does not take into consideration any tissue attenuation and consequently, the dose calculation becomes less accurate. AAPM Report No. 220,¹⁵ introduced a more robust size metric defined as the water-equivalent diameter (D_w). Tissue attenuation could be evaluated from the average CT number value in the patient field of view (FoV) to enable variations in patient inhomogeneity.

Assessment of either D_{eff} or D_w can be performed once the scanning procedure is completed, but it is time-consuming. Recently, new methods to automatically calculate D_{eff} and D_w have been reported.^{16,17} A comprehensive study of the relationships between D_{eff} and D_w and geometrical size is required to obtain an accurate patient dose.^{18,19} AAPM No. 204 reported the correlations of D_{eff} vs geometrical size in the abdominal region only.¹⁴ The aim of the current work is to establish robustly patient size in terms of D_{eff} and D_w as a function of AP and LAT dimensions in order to predict accurate patient dose for thoracic, abdominal, and pelvic regions from CT examinations.

Materials and Methods

CT Images

Axial clinical images from thoracic, abdominal and pelvic examinations were retrospectively collected in the digital imaging and communications in medicine (DICOM) format from two hospitals. We selected 47 images from patients who underwent thoracic examinations. They were scanned using a Siemens Sensation CT scanner (64 slices) with scanning parameters of 120 kVp tube voltage, 0.5 s rotation time, and 1.399 pitch. We used 79 abdominal images and 50 pelvic images scanned using a GE Optima CT580 with a tube voltage of 120 kVp, rotation time of 0.8 s, and 0.9375 pitch. Examples of images used in this study are shown in **Figure 1**. Patient ages were from 1 to 84 years old. Tube current modulation (TCM) was activated during all examinations to reduce the dose given.

Figure 1. Examples of images used in the current study, (a) thoracic, (b) abdominal, and (c) pelvic regions.

Determination of AP, LAT, D_{eff}, D_w, and ellipticity ratio

The AP, LAT, D_{eff}, and D_w values were automatically measured from axial CT images using IndoseCT version 20b software. Automated segmentation comprised thresholding, object recognition by edge detection, labeling, and calculation of the object area. The largest area of the objects was defined as the patient's perimeter.¹⁹ The software provided the effective diameter value from three alternative options, namely "Area", "Center", and "Max". We chose the AP and LAT dimensions at the position that gave a maximum value ("Max" option), as shown in **Figure 2**. The square root of the product of AP and LAT dimensions gives the D_{eff} value.¹⁴

$$D_{eff} = \sqrt{AP \times LAT} \quad \text{Eq. 1}$$

As reported in a previous study,¹⁷ D_{eff} calculations using the patient cross-sectional area or the maximum value showed no significant difference.¹⁷ The calculation of D_w utilized automated segmentation,¹⁶ whose results were used to crop the initial image. The D_w calculation referred to **Equation 2**:¹⁵

$$D_w = 2 \sqrt{\left[\frac{1}{1000} HU(x, y)_{ROI} + 1 \right] \frac{A_{ROI}}{\pi}} \quad \text{Eq. 2}$$

where A_{ROI} represents the patient area after cropping and $HU(x, y)_{ROI}$ is the mean CT number inside the patient's region of interest (ROI). A previous study showed that the percentage

difference between automatic and manual calculation was less than 0.5%.¹⁶

This current work also calculated the ellipticity ratio (r) for all three regions. The ellipticity ratio is calculated as the ratio of LAT to AP dimension. We reported the average, standard deviation, minimum and maximum values of ellipticity ratio in the three regions.

Correlations of AP, LAT, D_{eff}, and D_w

AAPM Report No 204 provided curves of D_{eff} as functions of AP, LAT, and AP + LAT to estimate the specific geometrical-size conversion factor in the abdominal region. D_{eff} and AP, and D_{eff} and LAT were correlated with each other as second-order polynomial functions (**Equation 3**).

$$y = ax^2 + bx + c \quad \text{Eq. 3}$$

D_{eff} was correlated with AP+LAT as a linear function (**Equation 4**):

$$y = ax + b \quad \text{Eq. 4}$$

Regression analysis and scatter data points were used to characterize the dependency of D_{eff} and D_w on AP, LAT, and AP+LAT dimensions. R-squared (R²) values were also provided in this study to assess the concurrence level of the correlation between D_{eff} and D_w to the geometrical-size functions.

Figure 2. IndoseCT 20b offers automatic calculations of AP, LAT, and D_{eff} calculation by three alternative options namely "Area", "Center", and "Max". We opted to use the "Max". The software also offers automatic D_w calculation by choosing "The water-equivalent diameter".

Results

Thoracic region

Figure 3 shows D_{eff} and D_w plotted against geometrical sizes (LAT, AP and LAT+AP) for the thoracic region. The best fitted lines for D_{eff} and D_w in terms of LAT or AP are second-order polynomial fits. The coefficients are shown in each figure, together with the coefficients of determination, R^2 . The best fit lines for D_{eff} and D_w in terms of AP+LAT are first-order polynomials, and the corresponding coefficients and R^2 values are given within each figure. **Figure 3g** shows that D_w is linearly related to D_{eff} with a slope of 0.8447, an intercept of 0.6733, and R^2 of 0.9474. The average patient sizes are tabulated in **Table 1**. In the thoracic region, the average value of D_{eff} is greater than D_w .

Table 1. Patient size obtained from the current study in the thoracic region.

Dimensions	Mean $\pm$ Std. Dev (cm)	Range (cm)
LAT	30.39 $\pm$ 4.42	16.03 – 38.22
AP	18.87 $\pm$ 2.89	11.25 – 24.40
AP + LAT	49.26 $\pm$ 7.13	27.28 – 62.62
D_{eff}	24.08 $\pm$ 3.53	13.54 – 30.97
D_w	21.01 $\pm$ 3.14	12.21 – 26.13

Figure 3. D_{eff} and D_w values as functions of the geometrical-size for the thoracic region, (a) D_{eff} vs LAT, (b) D_w vs LAT, (c) D_{eff} vs AP, (d) D_w vs AP, (e) D_{eff} vs AP+LAT, (f) D_w vs AP+LAT, and (g) D_w vs D_{eff} .

Abdominal region

The correlations between D_{eff} and D_w as functions of geometrical diameters in the abdominal region are shown in **Figure 4**. The best-fitted lines for D_{eff} and D_w in terms of LAT or AP are second-order polynomial fits, and the coefficients and R^2 values are shown in each figure. The lines are curved in the opposite directions to those for the thoracic regions. The best fit lines for D_{eff} and D_w in terms of AP+LAT are first-order polynomials, and the corresponding coefficients and R^2 values are given within each figure. **Figure 4g** shows that D_w is linearly related to D_{eff} with a slope of 0.9599, an intercept of 0.6831, and R^2 of 0.9908. **Table 2** shows the range of patient dimensions for the abdominal region. The average values of D_w and D_{eff} are similar.

Table 2. Patient size obtained from the current study in the abdominal region.

Dimensions	Mean $\pm$ Std. Dev (cm)	Range (cm)
LAT	29.71 $\pm$ 3.48	22.53 – 39.94
AP	21.47 $\pm$ 3.43	14.32 – 29.2
AP + LAT	51.18 $\pm$ 6.76	37.4 – 69.14
D_{eff}	25.97 $\pm$ 3.55	18.67 – 35.90
D_w	25.61 $\pm$ 3.42	18.70 – 35.09

Figure 4. D_{eff} and D_w values as functions of geometrical-size for abdomen region, (a) D_{eff} vs LAT, (b) D_w vs LAT, (c) D_{eff} vs AP, (d) D_w vs AP, (e) D_{eff} vs AP+LAT, (f) D_w vs AP+LAT, and (g) D_w vs D_{eff} .

Pelvic region

The correlations between D_{eff} and D_w as functions of geometrical diameters in the abdominal region are shown in **Figure 5**. All graphs are best fitted with downward curving second-order polynomial functions. **Figure 5g** shows that D_w is linearly related to D_{eff} with a slope of 0.9205, an intercept of 2.1814, and R^2 of 0.9795. **Table 3** shows the range of patient dimensions for the pelvic region. The average values of D_w and D_{eff} are also similar in the pelvic region.

Table 3. Patient size obtained from the current study in the pelvic region.

Dimensions	Mean $\pm$ Std. Dev (cm)	Range (cm)
LAT	32.47 $\pm$ 3.43	26.06 – 38.69
AP	19.48 $\pm$ 2.54	13.19 – 24.52
AP + LAT	51.95 $\pm$ 5.79	39.50 – 62.93
D_{eff}	25.96 $\pm$ 2.78	19.08 – 30.97
D_w	26.08 $\pm$ 2.58	19.11 – 30.93

Figure 5. D_{eff} and D_w values as functions of geometrical-size for pelvic region, (a) D_{eff} vs LAT, (b) D_w vs LAT, (c) D_{eff} vs AP, (d) D_w vs AP, (e) D_{eff} vs AP+LAT, (f) D_w vs AP+LAT, and (g) D_w vs D_{eff} .

Table 4. Calculation of elliptical ratio ($r = \text{LAT}/\text{AP}$) obtained from our study.

Body region	Mean $\pm$ Std. Dev	Range
Thorax	1.62 $\pm$ 0.11	1.42 - 1.87
Abdomen	1.40 $\pm$ 0.11	1.19 - 1.69
Pelvic	1.68 $\pm$ 0.11	1.43 - 1.99

Ellipticity ratio

The ellipticity ratios (LAT/AP) from the three regions i.e. thorax, abdomen, and pelvis, are tabulated in **Table 4**. The highest ellipticity ratio is found in the pelvic region ($r = 1.68 \pm 0.11$), followed by the thoracic region ($r = 1.62 \pm 0.11$), and the smallest value is found in the abdominal region (1.40 ± 0.11). The ellipticity ratio obtained from this current work is more than unity which means the LAT dimension is longer than AP dimension. It is consistent with the images used as we have shown in **Figure 1**.

Discussions

The SSDE is the most robust metric to quantify the radiation dose received by a patient from a CT scanner. It is obtained by normalizing the CT scanner output (CTDI_{vol}) with a size-conversion factor (f). The size-conversion factor was derived from four independent cohort investigators. Two of the investigators derived it using Monte Carlo-based measurement, whereas the others employed physical phantoms.¹⁴ The utilization of the size-conversion factor was based on the geometrical diameter, which in this case refers to the effective diameter (D_{eff}). The D_{eff} value was calculated as the square root of the product of the AP and LAT dimensions. Usually, AP and LAT dimensions are measured manually or automatically from CT radiographs or axial CT images.²⁰⁻²²

A metric that incorporates both geometrical size and tissue composition is the water-equivalent diameter (D_w). The calculation of SSDE based on D_w can generally be done automatically. Dose monitoring systems are available and used in many radiology centers, and many of them automatically calculate SSDE. Some of them rely on patient dimensions calculated from CT radiographs, but some can calculate water equivalent diameter from axial images.²³⁻²⁵ The D_{eff} for chest examination can be corrected for the presence of lung tissue to give a more accurate estimation of SSDE.²⁶

Approximating D_{eff} using only one dimension, AP or LAT, would be very helpful in the clinical environment so that it could be estimated from the CT radiograph which is usually scanned in one direction. It can be obtained in this way, if the relationships between AP and D_{eff} , or LAT and D_{eff} , are known. AAPM Report No 204 provided these relationships, but only for the abdominal region. The current study provides the relationships for three regions, i.e. thorax, abdomen, and pelvis, but not for the head.

The relationships between D_{eff} and LAT, AP, as well as AP+LAT dimensions for the thorax region, are shown in **Figure**

3a, **Figure 3c**, and **Figure 3e**, respectively. D_{eff} vs LAT dimension generates an upward curvature, D_{eff} vs AP generates a downward curvature, and D_{eff} and AP+LAT generate a linear correlation. The three curves all show strong correlations.

We also established the relationships between D_w and AP and LAT dimensions, which make it easier to predict dose more accurately. The relationships between D_w and LAT, AP, and AP+LAT for the thorax region are shown in **Figure 3b**, **Figure 3d**, and **Figure 3f**. In the thoracic region, D_{eff} is greater than D_w , because the lung mostly consists of air having very much lower pixel values than water.

For the abdominal region, the relationship of D_{eff} and D_w as functions of LAT, AP, and AP+LAT are shown in **Figure 4**. Our results are different from those given in AAPM Report No 204. In the latter report, the curve of D_{eff} vs LAT had a slightly upward curvature, while our study finds a downward curvature. Similarly, for the D_{eff} vs AP curve, the AAPM reported slightly downward curvature, while our study finds a slightly upward curve. The data used by AAPM was obtained from a mathematical pediatric phantom, a water-equivalent cylindrical phantom, and CT examinations of pediatric patients.²⁷⁻²⁹ The geometric size on the AAPM curves represented a wide range of diameters (from LAT = 12.7 cm and AP = 9.8 cm to LAT = 44 cm and AP = 36 cm). Our study used patients with a more limited range of sizes (from LAT = 22.53 cm and AP = 14.32 cm to LAT = 39.94 cm and AP = 29.20 cm). We believe the slightly different trendlines are due to the different ranges of data. In addition, Burton et al.¹⁹ reported the linear correlations of D_{eff} vs LAT and D_{eff} vs AP in the abdomen region, which confirmed that the trendlines are dependent on the data used. We found that the D_{eff} value is similar to D_w in the abdominal region. This is because the composition of the abdomen is mostly soft tissue with CT numbers similar to water.

The relationships of D_{eff} and D_w as functions of the geometrical sizes for the pelvic regions are shown in **Figure 5**. All the curves have downward curvature. In the pelvic area, the average value of D_w is similar to D_{eff} . Previously, we expected that the average value of D_w will be higher than D_{eff} because the composition of the pelvis is soft tissue and dense bone with CT numbers more than +1000 HU. However, the results of the current study revealed that the D_w is only 0.14 cm higher than the D_{eff} . On the other hand, D_w is similar to D_{eff} . This may be due to the existence of fat with the -150 to -50 HU range.³⁰ Combination of bone and fat may lead the D_w is similar with the D_{eff} .

Table 5. R^2 value and best fit parameters between D_{eff} and AP, D_{eff} and LAT, D_{eff} and (AP+LAT), D_w and AP, D_w and LAT, D_w and (AP+LAT), and D_w vs D_{eff} for the thoracic region.

	$D_{\text{eff}} - \text{LAT}$	$D_w - \text{LAT}$	$D_{\text{eff}} - \text{AP}$	$D_w - \text{AP}$	$D_{\text{eff}} - (\text{AP}+\text{LAT})$	$D_w - (\text{AP}+\text{LAT})$	$D_w - D_{\text{eff}}$
R^2 value	0.9379	0.8631	0.9528	0.8483	0.9841	0.8913	0.9474
a value	0.0018	0.0059	-0.0402	-0.0364	0.4905	0.4162	0.8447
b value	0.6704	0.3324	2.6330	2.3064	0.0852	0.5079	0.6733
c value	1.9676	5.3512	-10.9508	-9.2449	-	-	-

Table 6. R^2 value and fit parameters between D_{eff} and AP, D_{eff} and LAT, D_{eff} and (AP+LAT), D_w and AP, D_w and LAT, D_w and (AP+LAT), and D_w vs D_{eff} for the abdominal region.

	$D_{\text{eff}} - \text{LAT}$	$D_w - \text{LAT}$	$D_{\text{eff}} - \text{AP}$	$D_w - \text{AP}$	$D_{\text{eff}} - (\text{AP}+\text{LAT})$	$D_w - (\text{AP}+\text{LAT})$	$D_w - D_{\text{eff}}$
R^2 value	0.9495	0.9485	0.9555	0.9406	0.9928	0.9844	0.9908
a value	-0.0155	-0.0151	0.0098	0.0096	0.5229	0.5021	0.9599
b value	1.9387	1.8818	0.5898	0.5510	-0.7946	-0.0890	0.6831
c value	-17.7922	-16.7509	8.6868	9.2149	-	-	-

Table 7. R^2 value and fit parameters between D_{eff} and AP, D_{eff} and LAT, D_{eff} and (AP+LAT), D_w and AP, D_w and LAT, D_w and (AP+LAT), and D_w vs D_{eff} for the pelvic region.

	$D_{\text{eff}} - \text{LAT}$	$D_w - \text{LAT}$	$D_{\text{eff}} - \text{AP}$	$D_w - \text{AP}$	$D_{\text{eff}} - (\text{AP}+\text{LAT})$	$D_w - (\text{AP}+\text{LAT})$	$D_w - D_{\text{eff}}$
R^2 value	0.8914	0.8618	0.9290	0.9053	0.9690	0.9401	0.9795
a value	-0.0151	-0.0197	-0.0143	-0.0134	-0.0052	-0.0061	0.9204
b value	1.7506	1.9690	1.6040	1.4839	1.0069	1.0630	2.1814
c value	-14.5654	-16.8348	0.2306	2.3474	-	-	-

The fit parameters obtained from the current work are summarized in **Tables 5-7**. It shows that R^2 values for the relationships between D_{eff} and geometrical sizes are greater than 0.9, and greater than 0.8 for the relationships between D_w and geometrical sizes. This confirms that an accurate estimation of D_{eff} , and even D_w , can be obtained by using only one dimension, either AP or LAT. However, estimating D_{eff} and D_w using the two dimensions, AP and LAT, is more accurate if both are available. Although D_w can be estimated with the relationships obtained from the current study, it is suggested that its value should be obtained directly from the image using **Equation 2**. However, calculating the patient area and the mean HU value in the patient image is not easy in a clinical setting.

This study also shows a strong ($R^2 > 0.9$) correlation of D_w with D_{eff} . We mentioned that D_w is the more robust indicator in estimating the dose received because it takes into account the tissue composition.³¹ D_w can be easily estimated from D_{eff} because of the linear relationship built between the two indicators.

In this study, we calculated the elliptical ratios for the three regions. Our elliptical ratios are consistent with Burton et al.¹⁹, who reported that the elliptical ratios for the thorax and abdomen were 1.51 ± 0.21 and 1.38 ± 0.20 , respectively. Our elliptical ratio for the pelvic region was 1.68 ± 0.11 . Burton et al.¹⁹ did not report the elliptical ratio in this region but reported 1.48 ± 0.22 for abdomen-pelvis.

This study has several limitations. It is a retrospective study based on limited numbers (176) of patient images from the thorax, abdomen, and pelvic regions of local (Indonesian) patients. Further investigations are required for a larger range of LAT and AP dimensions.

Conclusion

The relationships between the constructed diameters, the effective diameter (D_{eff}) and water-equivalent diameter (D_w), and the basic geometric diameters, lateral (LAT), anterior-posterior (AP), and AP+LAT dimensions, were studied using 47 thoracic images, 79 abdominal images, and 50 pelvic images. The R^2 values for the relationships between D_{eff} and the geometrical sizes were greater than 0.9, and were greater than 0.8 for the relationships between D_w and the geometrical sizes. We found that an accurate estimation of D_{eff} and D_w can be obtained by using only one dimension, either AP or LAT. We also found that in the thoracic region the average value of D_{eff} is higher than D_w , in the abdominal and pelvic regions the average values of D_{eff} and D_w are similar. Since D_w includes tissue attenuation, it is the more accurate parameter for CT dose estimation. Fortunately, D_w has strong linear relationships with the other dimensions, and can readily be estimated from them.

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Conflict of Interest

Dr. Choirul Anam is one of the IndoseCT developers. However, the IndoseCT is not commercially available and it can be made available on request for research purposes. The rest of the authors have no conflicts of interest to disclose.

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