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Effect of Phantom Size and Tube Voltage on the Size-Conversion Factor for Patient Dose Estimation in Computed Tomography Examinations

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ABSTRACT

Introduction: This study aimed to establish the conversion factors to normalize the output dose of volumetric computed tomography dose index (CTDIvol) to the patient dose (i.e. size-specific dose estimate (SSDE)) for various phantom diameters and tube voltages.

Material and Methods: In-house cylindrical acrylic phantoms with physical diameters ranging from 8 to 40 cm were developed in this study. Each phantom had a hole in the center and four holes in the peripheral areas. The phantoms were scanned by a Siemens Somatom Definition AS CT Scanner using different tube voltages (i.e. 80, 100, 120, and 140 kVps) and with 200 mAs and 10 mm slice thickness. In addition, the doses in every hole and phantom were measured using a Raysafe X2 CT Sensor. The weighted SSDE (SSDEw) values were calculated using the five holes in every measurement. The size-conversion factors for the body and the head CTDI phantoms were established by dividing the SSDEw for various sizes with the SSDEw at the water-equivalent diameter of 33.90 cm and 16.95 cm, respectively.

Results: The results revealed that the size-conversion factor exponentially decreased with an increase in the phantom size. It was also found that the size-conversion factor was affected by the tube voltages. Furthermore, the different size-conversion factor between 80 and 140 kVp was more than 15% in very thin and obese patients.

Conclusion: Higher accuracy of the size-specific dose estimation can be achieved considering the impact of the tube voltages beside the size of the patient.

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Introduction

Computed tomography (CT) scanner is one of the imaging modalities in the Radiology Department that can produce images of patients in axial, coronal, and sagittal planes [1]. With the help of a CT scanner, it is possible to depict the inner parts or organs in each slice with high-quality images [2]. The CT scanner can be applied in a wide range of indications from trauma to cancer diagnoses. However, the use of CT certainly provides a high radiation dose, compared to other diagnostic imaging modalities [3-5].

Until the 2010s, the dose of CT scanner was expressed in a metric of volumetric computed tomography dose index (CTDIvol) [6, 7]. This metric is an only index to quantify the output dose of the CT scanner, not to quantify the radiation dose of the patient [8]. The metric to quantify the patient dose in CT examination had just been developed in 2011 following the American Association of Physicists in Medicine (AAPM) Report No. 204 [9]. In that report, the AAPM introduced the patient dose estimation from CT scans known as size-specific dose estimates (SSDE) [9]. To quantify the patient's radiation dose, CTDIvol has to be normalized by the size-conversion factor. Technically, the SSDE is calculated by multiplying the CTDIvol value and the size-conversion factor (f) [10]. The size of a patient can be expressed in the effective diameter (Deff) [10] or more comprehensively be expressed in the water-equivalent diameter (Dw) of the patient [11].

In a practical calculation, the SSDE can be carried out on the patient's image using software, such as IndoseCT [12]. Recently, the vendor (General Electric Inc., Milwaukee, USA) provides a DoseWatch™ to automatically calculate SSDE from the medical device or picture archiving and communication system [13].

The SSDE nowadays is widely used in clinical practice. The AAPM Report No. 204 also provided the size-conversion factors to easily normalize the

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CTDIvol to SSDE [9]. The AAPM reported that the uncertainties of SSDE with this technique are within 20% [9]. Although the AAPM was aware of the SSDE as the impact of the tube voltage variations, for practical consideration, the AAPM only provided a single graph of size-conversion factor regardless of the tube voltage [9]. Therefore, it is essential to establish a size-conversion factor for various tube voltages.

Many researchers have evaluated the size-conversion factors by Monte Carlo studies [14-16] and showed the accuracy of the size-conversion factors. However, there is a dearth of research evaluating physical phantoms with various sizes in the literature. Previously, Andriani et al. [17] developed in-house phantoms with diameters from 8 to 40 cm and evaluated the size-conversion factor using those phantoms. In the aforementioned study, phantoms were made from acrylic material, and the measurements were carried out using a solid-state CT dose profiler with the Ocean software (RTI Electronics, Sweden) [17]. However, the design of phantoms had serious limitations since it had only one hole in the center of the phantoms instead of five holes [18]. Therefore, the developed size-conversion factor led to a wide discrepancy with that in the AAPM data. Accordingly, this method could not be used to accurately normalize CTDIvol to SSDE.

In the current study, phantoms of various diameters were improved to have five holes in each phantom. In total, four holes were added at the peripherals so that it could determine the distribution of radiation dose in the phantoms; moreover, it could be used to measure dose in the center phantom (SSDEc) and periphery of the phantom (SSDEp) allowing to calculate the weighted dose (SSDEw) in the phantoms [19]. As aforementioned, the AAPM reported that the patient dose was also affected by the tube voltages [9]; however, the size-conversion factor for various tube voltages was not included in the report [9]. Therefore, this study aimed to establish the size-conversion factors to normalize the CTDIvol to SSDE for various phantom diameters and tube voltages.

Materials and Methods

Phantom development

This study developed in-house phantoms that had various physical diameters of 8, 16, 24, 32, and 40 cm (Figure 1). The length of the phantoms was 15 cm. The phantoms were made from acrylic material as described previously [8]; however, four holes were added at the periphery of phantoms in addition to one hole in the center of phantoms. Since the doses were measured in the phantom with various diameters (d), the measured doses directly represented the size-specific dose estimate. With the help of these five holes, it is possible to measure SSDEc and SSDEp, and to calculate the SSDEw.

Size-specific dose estimate measurement

The phantoms were scanned using different tube voltages (i.e. 80, 100, 120, and 140 kVps) and a Siemens Somatom Definition AS CT Scanner (Siemens AG, Erlangen, Germany) (Figure 2a) with 200 mAs and 10 mm slice thickness. In addition, the doses in every hole of all various phantoms were measured using a Raysafe X2 CT Sensor (Raysafe Inc., Billdal, Sweden) (Figure 2b). The SSDEws were calculated using the five holes in every measurement.

The SSDEc and SSDEp were obtained from measurements at the center hole and peripheral of the phantom, respectively. The SSDEw was calculated using *Equation* (1):

$$SSDEw = \frac{1}{3}SSDEc + \frac{2}{3}\overline{SSDEp} \quad (1)$$

where $\overline{SSDEp}$ is the mean of SSDEp.

The size-conversion factors for body CTDI phantom (f^{32}) and for head CTDI phantom (f^{16}) were calculated by normalizing the doses measured for every phantom diameter with doses measured for the physical diameters of 32 and 16 cm, respectively (*Equations* (2) and (3)).

$$f^{32} = \frac{SSDE_w^d}{SSDE_w^{32cm}} \quad (2)$$

$$f^{316} = \frac{SSDE_w^d}{SSDE_w^{16cm}} \quad (3)$$

The size-conversion factor was subsequently correlated with Dw for various tube voltages. The data were fitted with the exponential function (*Equation* (4)).

$$f = a \times e^{-b \times Dw} \quad (4)$$

The Dw [20] was calculated by *Equation* (5).

$$Dw = 2\sqrt{\left(\frac{1}{1000}\overline{HU} + 1\right)\frac{A}{\pi}} \quad (5)$$

A is the area of the phantom and $\overline{HU}$ signifies the mean pixel values of the phantom expressed in the Hounsfield unit. The size-conversion factor was compared with that in the AAPM Report No. 204 [9].

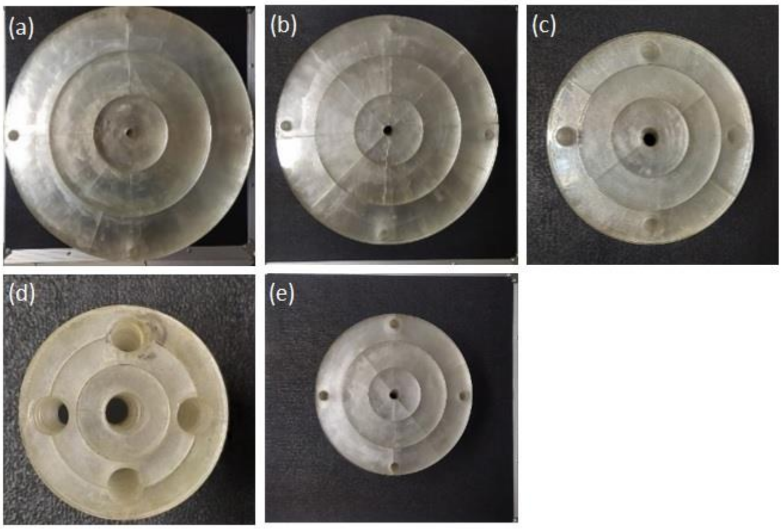

Figure 1. In-house acrylic phantoms with various diameters used in this study: 40 cm (a), 32 cm (b), 24 cm (c), 16 cm (d), and 8 cm (e). Noted: Images are depicted without scale.

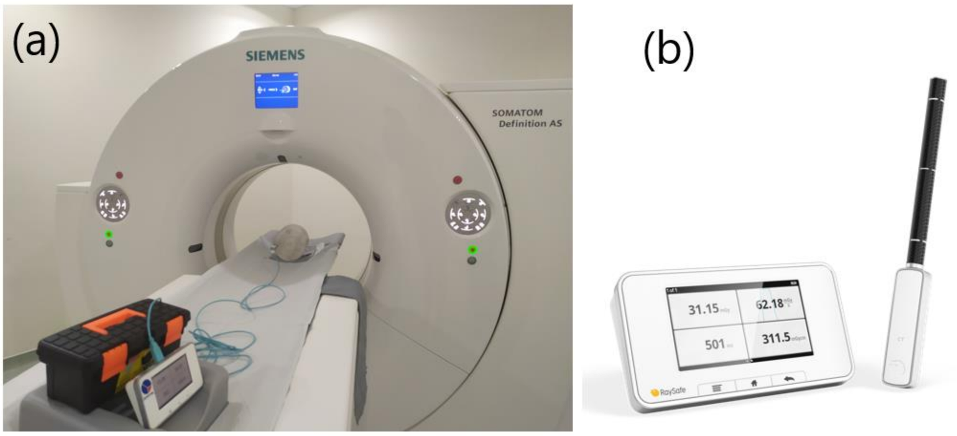

Figure 2. Siemens Somatom Definition AS CT scanner (2a), Raysafe X2 CT sensor (2b).

Results

Water-equivalent diameter of the phantoms

The Dws of the phantom for various physical Deffs were tabulated in Table 1. The Dw is about 6% higher than Deff. The pixel value of the acrylic material is 122.60±4.39 HU. As a comparison, the pixel value of the standard polymethyl methacrylate (PMMA) phantom is about 120 HU, and the Dws for the physical diameter of 16 and 32 cm are 16.89 and 33.92 cm, respectively [3]. Based on these results, the developed acrylic phantoms are very similar to the standard PMMA phantom.

Size-specific dose estimation

The SSDE values were calculated using the measurements of each hole (i.e. one hole at the center and four holes at the peripheral). The SSDEw was calculated using the SSDEc and SSDEp. Figure 3 illustrates the SSDEc, SSDEp, and SSDEw as a function of the Dw for a variation of tube voltages ranging from 80 up to 140 kVp. Moreover, it indicates that the doses (i.e., SSDEc, SSDEp, and SSDEw) decrease with an increase in the Dw. The SSDEc and SSDEp obtained the highest and lowest rates of decline, respectively; in addition, the SSDEw has an average decrease.

Table 1. Water-equivalent diameter of the phantom for various physical diameters

Effective diameter (cm)	Water-equivalent diameter (cm)	Difference (%)
8	8.48±0.02	6.00
16	16.95±0.03	5.94
24	25.43±0.05	5.96
32	33.90±0.07	5.94
40	42.08±0.08	5.20

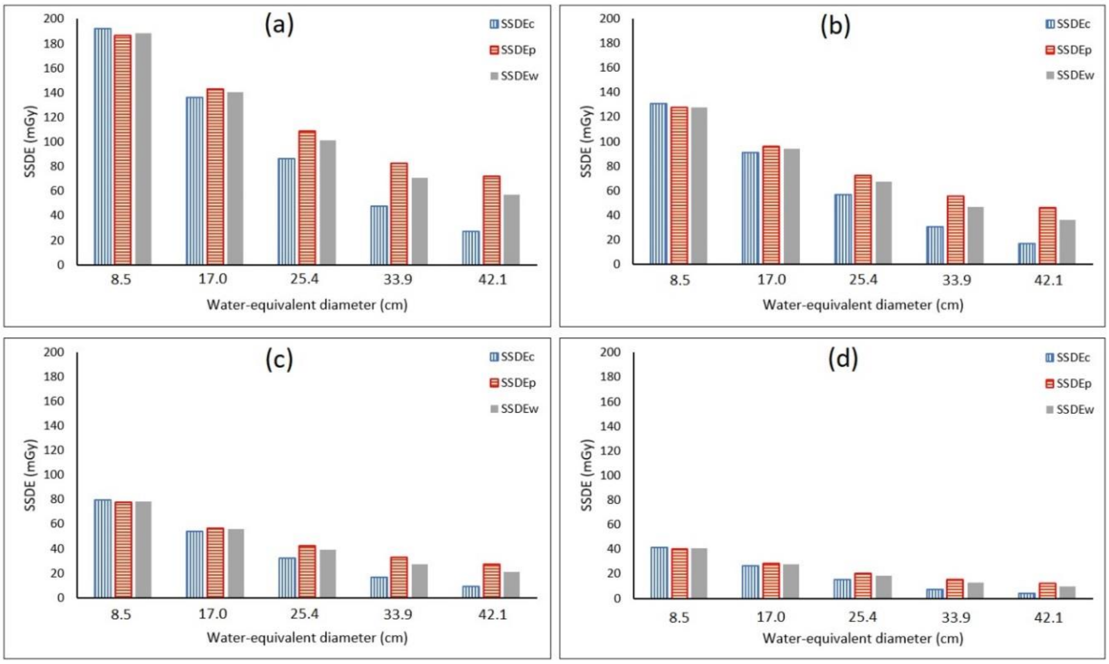

Figure 3. The SSDEc, SSDEp, and SSDEw as a function of the water-equivalent diameter for variation of tube voltages. 140 kVp (a), 120 kVp (b), 100 kVp (c), and 80 kVp (d).

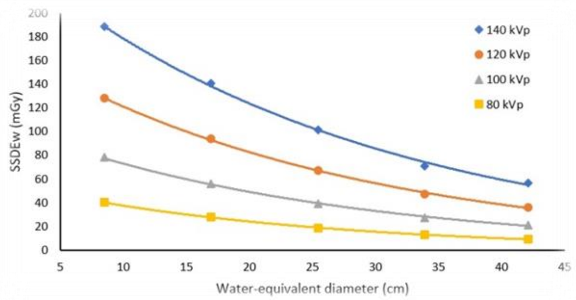

Figure 4. Values of SSDEw as a function of the water-equivalent diameter for various tube voltages

Figure 4 reveals the result of the SSDEw as a function of the Dw from a range of selected voltages. The dose increases with an increase in tube voltage. The highest dose (188.70 mGy) is obtained from Dw of 8.48 cm and the tube voltage of 140 kVp, and the lowest dose (9.44 mGy) is obtained from the Dw of 42.08 cm and the tube voltage of 80 kVp.

Validation of the results

In this study, *f*s are normalized to two Dws of 33.90 cm (f^{32}) and 16.95 cm (f^{16}). All data for all tube voltages are fitted with the exponential equation to produce a single graph of the size-conversion factor for the body phantom and a single graph of the size-conversion factor for the head phantom (Figure 5.) For validation, the results of the current study are compared with those in the AAPM [9]. It can be seen that the size-conversion factors from this study are comparable with those in the AAPM data with only small discrepancies for the body (5.5±4.1%) and head phantoms (1.3±0.9%). Table 2 indicates a, b, and R^2 values of the current study, compared to the AAPM data (i.e., *P*-values are 0.84 and 1.00 for body and head phantoms), whereas the R^2 values of the current study are more than 0.99.

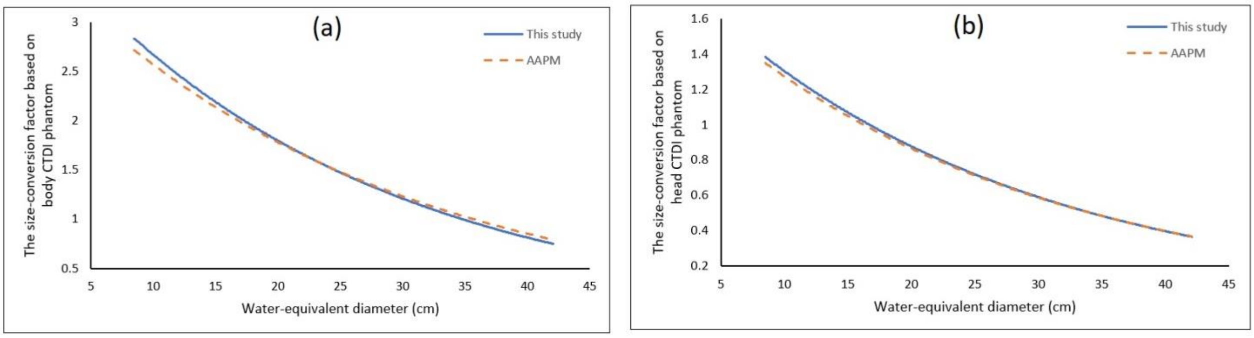

Figure 5. Comparison of the current study and AAPM regarding the size-conversion factor as a function of the phantom diameter

Table 2. Comparison of the current study and *AAPM regarding a, b, and R^2 values

	a	b	R^2
Body **CTDI phantom			
Present study	3.9365	0.041	0.998
AAPM [9]	3.7044	0.037	0.942
Head CTDI phantom			
Present study	1.9358	0.040	0.991
AAPM [9]	1.8748	0.038	0.967

* American Association of Physicists in Medicine
** Computed Tomography Dose Index

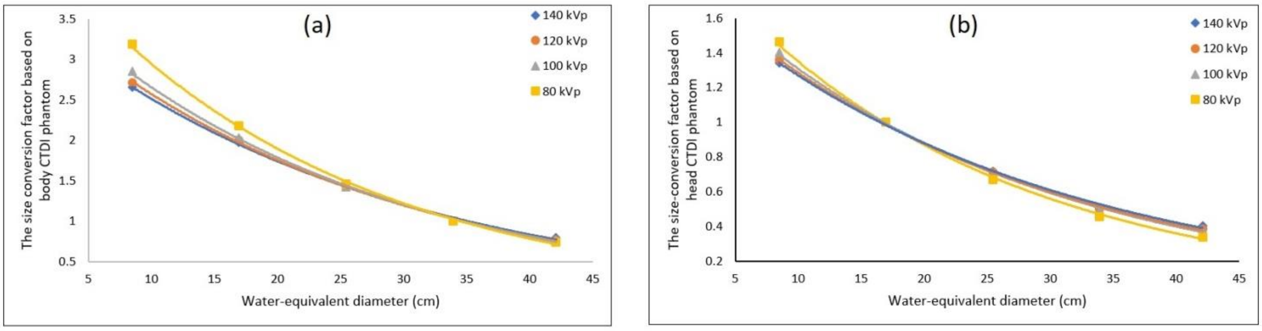

Figure 6. The size-conversion factor as a function of water-equivalent diameter from 8.48 to 42.08 cm for various tube voltages. The size-conversion factor is normalized at the water-equivalent diameter of 33.90 cm (6 a) and at the water-equivalent diameter of 16.95 cm (6 b).

The size-conversion factor for various tube voltages

Figure 6 shows the relationship between the size-conversion factors and Dw for various tube voltages, (a) body CTDI phantom, and (b) head CTDI phantom. From Figure (6a), it can be seen that in the smallest diameter (i.e., 8.48 cm), the discrepancy of the size-conversion factor between 80 and 140 kVps is 16.78%. Moreover, in the biggest diameter (42.08 cm), the discrepancy of the size-conversion factor between 80 and 140 kVps is 19.00%. Therefore, for an accurate result when normalizing CTDI to SSDE, the tube voltage should be considered, especially for very extreme patient size. The size-conversion factors for various tube voltages can be calculated using the parameters of a and b as tabulated in Tables 3 and 4. It shows that the R^2 is more than 0.99 for all tube voltages.

Table 3. a, b, and R^2 values for various voltages based on the body *CTDI phantom

Tube voltage (kVp)	a	b	R^2
80	4.5744	0.044	0.9981
100	3.9429	0.040	0.9979
120	3.7679	0.038	0.9984
140	3.6269	0.037	0.9965

* Computed Tomography Dose Index

Table 4. a, b, and R^2 values for various voltages based on head *CTDI phantom

Tube voltage (kVp)	a	b	R^2
80	2.0964	0.044	0.9981
100	1.9421	0.040	0.9979
120	1.8829	0.038	0.9984
140	1.8318	0.037	0.9965

* Computed Tomography Dose Index

Discussion

The purpose of this study was to establish the conversion factors to normalize the CTDIvol displayed in the CT console to SSDE for various phantom diameters and tube voltages. In-house cylindrical acrylic phantoms were developed with various physical diameters from 8 to 40 cm for this purpose. The phantoms were scanned with different tube voltages available in the CT machine (i.e. 80, 100, 120, and 140 kVps).

The current study was validated by the AAPM results, and the size-conversion factor increased exponentially with a decrease in the patient size if all input parameters were kept constant [21, 22]. There were only small discrepancies between the current study and the AAPM report regarding the magnitudes of the size-conversion factor [9] which were 5.5±4.1% and 1.3±0.9% for body and head phantoms, respectively. This indicates the accuracy of the in-house developed phantom and the method for measuring the size-conversion factor. The small discrepancies may arise from the fact that the AAPM data came from four different scanners, whereas the current study used only one CT scanner. This study revealed that although the size-conversion factor difference between scanners was small, the size-conversion factor was better to be derived from the CT machine itself for a more accurate estimation of patient dose in a particular CT machine.

The discrepancy between AAPM data and the current study can also be attributed to the fact that AAPM data are a combination of different size metrics (i.e. Deff and Dw) [9], whereas this study utilized only one metric of diameter, namely Dw. Therefore, in the body CTDI phantom, it can be seen that the unity of the size-conversion factor of AAPM data is at about 35 cm [9]; however, this value is at 33.9 cm diameter of the acrylic phantom in the present study. The Dw is considered a robust estimation of the patient's diameter since it not only characterizes the physical size of the patient but also the radiological size of the patient taking into account the attenuation properties of the patient or phantom [23].

The effect of tube voltage had been pointed out in the AAPM report No. 204 [9]. As in the current study, regarding the body CTDI phantom in the size-conversion factor at a small size, there is a big difference between the voltages 80 and 140 kVp. In the current study, the difference in the Dw of 8.48 cm (i.e. the size of new-born patients) is around 17%. On the contrary, regarding the head CTDI phantom in the size-conversion factor at a very big size, there is a big difference between the voltages 80 and 140 kVp (i.e. around 19%). These findings are consistent with the previous study by Li et al. [24]. Therefore, the tube voltage should be considered for an accurate result when converting CTDI to SSDE. However, the APPM did not report the size-conversion factors for various voltages.

For practical reasons, AAPM only reported the single size-conversion factor that can be used for all voltage variations on the available CT machine. Moreover, the AAPM recognized that the discrepancy of SSDE and the actual dose might be up to ± 20% [9]. In the current study, the size-conversion factor equations for voltage variations were reported taking voltage variations into account. This would facilitate more accurate dose calculation of patients, particularly from very thin to obese ones.

The main limitation of this study was the utilization of acrylic material sold in the market without any consideration of its density and homogeneity for phantom preparation. For more accurate results, it is recommended to evaluate the quality of the ingredients for phantom development. Moreover, the current study was only carried out on one CT scanner. Therefore, evaluations on various CT scanners would be useful for more comprehensive results.

Conclusion

According to the results obtained from this study, the size-conversion factor decreased exponentially with an increase in the phantom size. Moreover, the size-conversion factor was affected by the tube voltage. The different size-conversion factor between 80 and 140 kVp was more than 15% in very thin and obese patients. Accordingly, for more accurate dose estimation in very thin and obese patients, the impact of the tube voltage should be considered in the calculation of SSDE. It should be noted that the size-conversion factor is included in this study for various tube voltages.

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References

1. Kalender WA. X-ray computed tomography. Physics in Medicine and Biology. 2006; 51: 29‑43.
2. Seeram E. Computed tomography: Physical principles and recent technical advances. Journal of Medical Imaging and Radiation Sciences. 2010; 41: 87-109.
3. Martin CJ. Management of patient dose in radiology in the UK. Radiation Protection Dosimetry. 2011; 147: 355‑72.
4. Le Coultre R, Bize J, Champendal M, Wittwer D, Ryckx N, Aroua A, Trueb P, Verdun FR. Exposure of the Swiss population by radiodiagnostics: 2013 review. Radiation protection dosimetry. 2016;169(1-4):221-4.
5. Parry RA, Glaze SA, Archer BR. Typical patient radiation doses in diagnostic radiology. RadioGraphics. 1999; 19: 1289‑302.
6. Anam C, Fujibuchi T, Haryanto F, Widita R, Arif I, Dougherty G. An evaluation of computed tomography dose index measurements using a pencil ionisation chamber and small detectors. Journal of Radiological Protection. 2019; 39: 112‑24.
7. Figueira C, Di Maria S, Baptista M, Mendes M, Madeira P, Vaz P. Paediatric CT exposures: comparison between CTDIVOL and SSDE methods using measurements and Monte Carlo simulations. Radiation Protection Dosimetry. 2015; 165: 210-5.
8. Bashier EH, Suliman II. Multi-slice CT examinations of adult patients at Sudanese hospitals: Radiation exposure based on size-specific dose estimates (SSDE). La Radiologia Medica. 2018; 123: 424‑31.
9. AAPM. Size-specific dose estimates (SSDE) in pediatric and adult body CT examinations. AAPM Report no 204. 2011.
10. Anam C, Haryanto F, Widita R, Arief I. Automated estimation of patient's size from 3D image of patient for size specific dose estimate. Advanced Science, Engineering and Medicine. 2015; 7: 892-6.
11. Anam C, Haryanto F, Widita R, Arief I, Dougherty G. Automated calculation of water-equivalent diameter (DW) based on AAPM task group 220. Journal of Applied Clinical Medical Physics. 2016; 17: 320-33.
12. Anam C, Haryanto F, Widita R, Arif I, Dougherty G, McLean D. Volume computed tomography dose index (CTDIvol) and size-specific dose estimate (SSDE) for tube current modulation (TCM) in CT scanning. International Journal of Radiation Research. 2018; 16: 289-97.
13. Gao Y, Quinn B, Pandit-Taska N, Behr G, Mahmood U, Long D, et al. Patient-specific organ and effective dose estimates in pediatric oncology computed tomography. Physica Medica. 2018; 45: 146‑55.
14. Abuhaimed A, Martin CJ, Demirkaya O. Influence of cone beam CT (CBCT) scan parameters on size specific dose estimate (SSDE): A Monte Carlo study. Physics in Medicine and Biology. 2019; 64: 115002.

15. Nasir M, Pratama D, Anam C, Haryanto F. Calculation of size specific dose estimates (SSDE) value at cylindrical phantom from CBCT Varian OBI v1.4 X-ray tube EGSnrc Monte Carlo simulation based. Journal of Physics: Conference Series. 2016; 694: 012040.
16. Haba T, Koyama S, Kinomura Y, Ida Y, Kobayashi M. Influence of 320-detector-row volume scanning and AAPM report 111 CT dosimetry metrics on size-specific dose estimate: a Monte Carlo study. Australasian Physical & Engineering Sciences in Medicine. 2016; 39: 697‑703.
17. Andriani I, Budi WS, Sutanto H, Anam C. Analysis of the effect of phantom CT scan diameter variations on radiation dose with IndoseCT. International Journal of Allied Medical Sciences and Clinical Research. 2017; 7: 21-7.
18. Hossain A, Saha SK. Polymethyl Methacrylate phantom on CT imaging to evaluate size-specific effective dose in pediatric and adult body. International Journal of Biomedical Science and Engineering. 2015; 3: 82-8.
19. Kamezawa H, Arimura H, Arakawa H, Kameda N. Investigation of a practical patient dose index for assessment of patient organ dose from cone-beam computed tomography in radiation therapy using a Monte Carlo simulation. Radiation Protection Dosimetry. 2018; 181: 333-42.
20. Anam C, Arif I, Haryanto F, Widita R, Lestari FP, Adi K, et al. A simplified method for the water-equivalent diameter calculation to estimate patient dose in CT examinations. Radiation Protection Dosimetry. 2019; 185: 42-9.
21. Menke J. Comparison of different body size parameters for individual dose adaptation in body CT of adults. Radiology 2005; 236: 565‑71.
22. Schindera ST, Nelson RC, Toth TL, Nguyen GT, Toncheva GI, DeLong DM, et al. Effect of patient size on radiation dose for abdominal MDCT with automatic tube current modulation: Phantom study. American Journal of Roentgenology. 2008; 190: 100‑5.
23. Anam C, Fujibuchi T, Toyoda T, Sato N, Haryanto F, Widita R, et al. A simple method for calibrating pixel values of the CT localizer radiograph for calculating water-equivalent diameter and size-specific dose estimate. Radiation Protection Dosimetry. 2018; 179: 158‑68.
24. Li X, Yang K, Liu B. A study of the midpoint dose to CTDIvol ratio: Implications for CT dose evaluation. Medical Physics. 2016; 43(11): 5878-88.