Scatter index measurement using a CT dose profiler

Choirul Anam[1,2,*], Freddy Haryanto[2], Rena Widita[2], Idam Arif[2], Toshioh Fujibuchi[3], Takatoshi Toyoda[3], and Geoff Dougherty[4]

[1]Department of Physics, Faculty of Mathematics and Natural Sciences, Diponegoro University, Jl. Prof. Soedarto SH, Tembalang, Semarang 50275, Central Java, Indonesia
[2]Department of Physics, Faculty of Mathematics and Natural Sciences, Bandung Institute of Technology, Ganesha 10, Bandung 40132, West Java, Indonesia
[3]Department of Health Sciences, Faculty of Medical Sciences, Kyushu University, 3-1-1 Maidashi, Higashi-ku, Fukuoka, Fukuoka 812-8582, Japan
[4]Applied Physics and Medical Imaging, California State University Channel Islands, Camarillo, CA 93012, USA.

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

Received July 25 2017
Revised August 31 2017
Accepted for publication September 02 2017
Published September 04 2017

Abstract: The CT dose index (CTDI) is usually measured using a pencil chamber with a length of 100 mm on a CTDI phantom with a length of 150 mm. The scattering radiation dose beyond 100 mm is usually still significant despite using a small beam width (below 10 mm). This study aims to measure the scattering index of CT dose for several variations of input parameters. The scatter index measurements were performed on a multi-slice CT (MSCT) Alexion™ using a CT dose profiler connected to a Black Piranha electrometer (RTI Electronic, Sweden). The measurements used the helical mode and a beam width of 2 x 4 mm, and resulted in 150 mm dose profiles. Values of $CTDI_{150}$, $CTDI_{130}$ and $CTDI_{100}$ were calculated and used to obtain values of the scatter indices (SI_{130} and SI_{150}). We varied input parameters, such as tube voltage, tube current, and pitch, and used two types of CTDI phantoms, i.e. body and head. In the tube voltage variation (from 80 to 135 kVp), we found SI_{130} and SI_{150} values of 1.13 ± 0.01 and 1.19 ± 0.01 for the body CTDI phantom; and SI_{130} and SI_{150} values of 1.08 ± 0.01 and 1.11 ± 0.01 for the head CTDI phantom. For tube current variations from 25 to 120 mA, and pitch variations from 0.75 to 1.5, SI_{130} and SI_{150} values were 1.14 ± 0.00 and 1.20 ± 0.00 for the body CTDI phantom; and 1.08 ± 0.00 and 1.11 ± 0.00 respectively for the head CTDI phantom. We showed that the more frequently used $CTDI_{100}$ value is too small because it ignores scattering beyond the 100 mm boundary, even for beam widths less than 10 mm. The scatter index values were strongly influenced by the size of the CTDI phantom, and were slightly affected by the tube voltage. Variations in tube currents and pitch did not affect the value of the scatter index. The scatter index values of SI_{130} and SI_{150} were significantly different, and suggests that the use of SI_{150} is even more appropriate for describing the scattering dose.

Keywords*: scatter index, CT dose index, CT scan, CT dose profiler*

1. Introduction

The radiation dose produced by a CT scan of a particular slice is a combination of primary radiation and scatter radiation from other slices.[1,2] In clinical CT examinations, it is usually obtained from a number of slices from tens to hundreds.[3,4] Indeed, the dose from a certain slice due to scattering radiation from other slices may be greater than from its primary radiation.[5] Thus, the measurement of the radiation dose on a slice is very complicated. Typically multiple scans of axial modes on the phantom are measured using thermo-luminescence detectors (TLDs) to obtain a combined primary dose and all the scatter doses from all scanned slices.[6] From these multiple scans, the dose profile curve is obtained. The average dose in the center of phantom is calculated from the mean value of the profile sections, and is called the multiple scan average dose.[7,8]

In practice, the average dose in the center of a cylindrical phantom can be estimated by only a single slice scanning of the axial mode using a sufficiently long pencil detector such that the combined primary dose and the scattering dose to a certain distance can be measured at once.[6] If the measured dose is divided by the beam width then a dose value comparable to the value of the multiple scan average dose is obtained. This approach produces an index dose called the CT dose index (CTDI).[9] The CTDI value is complex and strongly influenced by many CT scan parameters, such as tube voltage, tube current, rotation speed, pitch, and slice thickness.[7] The CTDI is the index used to quantify the output radiation dose of a CT scan, and so it can be used to compare the output dose among different CT scanners. It is also commonly used for acceptance tests and quality control of CT scanners.[6] The length of the pencil chamber commonly used in measurement is 100 mm, so the dose index is often called $CTDI_{100}$.[8] In a CT scanner with a beam width of less than 10 mm, the $CTDI_{100}$ is acceptable. However, for multi-slice CT (MSCT) technologies that have beam widths close to or greater than 100 mm,[10-13] the accuracy of $CTDI_{100}$ is questionable and it may not reasonably reflect patient doses.[14-17] A more realistic approach is to use a pencil chamber that is much longer than 100 mm,[18] or use a combination of several pencil chambers.[18,19]

An alternative is to use a small ion chamber or a small solid state detector that is moved along the z-axis during the scanning process.[1,20,21] However, the use of a small moving detector cannot be done with a single scan of the axial mode.[1,20] Instead, the helical mode must be used.[21] With a small moving detector it is possible to obtain a dose profile from a single helical scan with the desired scanning length.[21] By using a dose profile for any given scanning length, it is possible to evaluate the scattering dose for a specific scan length and compare it to the 100 mm scan length. Comparison of $CTDI_{130}$ with $CTDI_{100}$ is called a scatter index (SI) or, more specifically, scatter index 130 (SI_{130}).[20] Scatter indices are usually measured for beam widths greater than 10 mm. However, according to Boone[15] using Monte Carlo simulations, the scattering dose measured for beam widths smaller than 10 mm is still significant. This study evaluated the scatter index for beam widths less than 10 mm for different CT input parameters. We also expanded the scatter index to scatter index 150 (SI_{150}).

2. Materials and methods

2.1. Experimental set-up

The scatter index was calculated from the measured dose profiles on a multi-slice CT (MSCT) Alexion™ installed at the Department of Health Sciences, Faculty of Medical Sciences, Kyushu University, Japan. Measurements were performed using a CT dose profiler (RTI Electronic, Sweden) (Figure 1a), Black Piranha electrometer (RTI Electronic, Sweden) (Figure 1b), netbook with Ocean software (RTI Electronic, Sweden) and CTDI phantoms (Figure 1c-d).

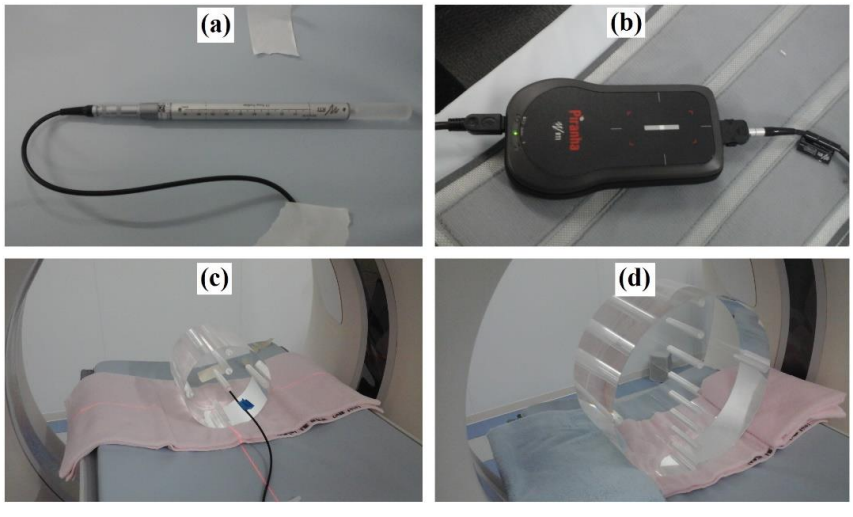

Figure 1. (a) CT dose profiler, (b) Black Piranha electrometer, (c) head CTDI phantom, (d) body CTDI phantom.

The CT dose profiler is an advanced point dose probe that is contained within a thin-walled aluminum tube filled with plastic. It has the shape of pencil ionization chamber, so that it can be inserted into holes in a CTDI phantom.[22] The CT dose profiler uses a very small solid-state detector (0.25 mm), placed at 30 mm from the end of the probe. The probe is extended with an extension piece made of 45 mm PMMA, so that the detector will be centered in the middle of a 150 mm CTDI phantom when the end of the extension reaches the end of the phantom.[22] The CT dose profiler is connected to a Black Piranha electrometer (of size 133 x 75 x 26 mm and weight about 400 g), whose output is recorded by a netbook with Ocean software. The CT dose profiler recorded the dose in small time intervals (16.0595 ms).

There are two sizes of cylindrical CTDI phantom, with diameters of 160 mm (Figure 1c) and 320 mm (Figure 1d). They are made of PMMA material, and both are 150 mm long. Each has a hole in the middle and several holes along the edge, although in this study, measurements were made using only the central hole.

2.2. Scatter index

The scan is performed in helical mode with 1 s rotation time, beginning precisely at the beginning of the CTDI phantom and ending at the end of phantom, to obtain 150 mm-dose profiles. A typical dose profile is shown in Figure 2. If the profile is integrated along X and divided by the beam width then the $CTDI_X$ value is obtained.

$$CTDI_X = \frac{1}{Nd}\int_{z=-X/2}^{+X/2} D(z)dz \quad (1)$$

where N is the number of CT detectors and d is the width of each detector used for data acquisition. The product of N and d is the beam width. The integration length of the dose profile (D (z)) determines the CTDI value obtained, i.e. for X = 100 mm, $CTDI_{100}$ is obtained, for X = 130 mm, $CTDI_{130}$ is obtained, and if the profile is integrated along X = 150 mm, $CTDI_{150}$ is obtained.

The scatter index is the ratio between the $CTDI_X$ and $CTDI_{100}$ when measurements are made in a phantom.[20]

$$SI_X = \frac{CTDI_X}{CTDI_{100}} \quad (2)$$

For scatter index calculations, X is usually 130 mm and the scatter index is known as scatter index 130 (SI_{130}). In this study, we also calculated the scatter index for X =150 mm, which we called scatter index 150 (SI_{150}).

This study was performed on a beam width less than 10 mm, i.e. 2 x 4 mm. Scatter index measurements are usually performed for beam widths greater than 10 mm, since the scatter radiation in this beam width is significant,

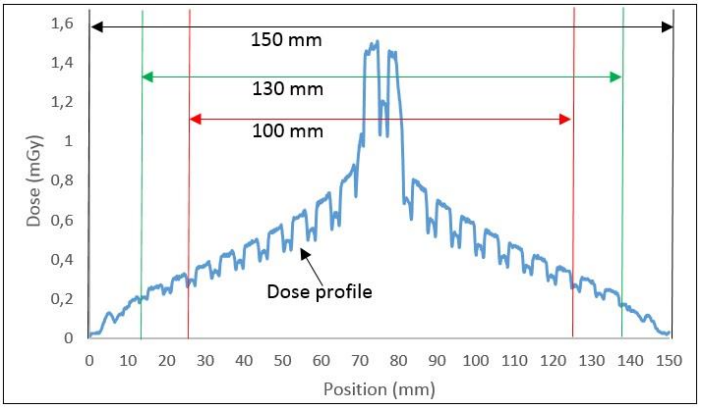

Figure 2. Dose profile obtained using the CT dose profiler. CTDI was obtained as an integral of dose profile divided by beam width (Nd). Integration was performed along 100, 130 and 150 mm lengths to obtain $CTDI_{100}$, $CTDI_{130}$ and $CTDI_{150}$.

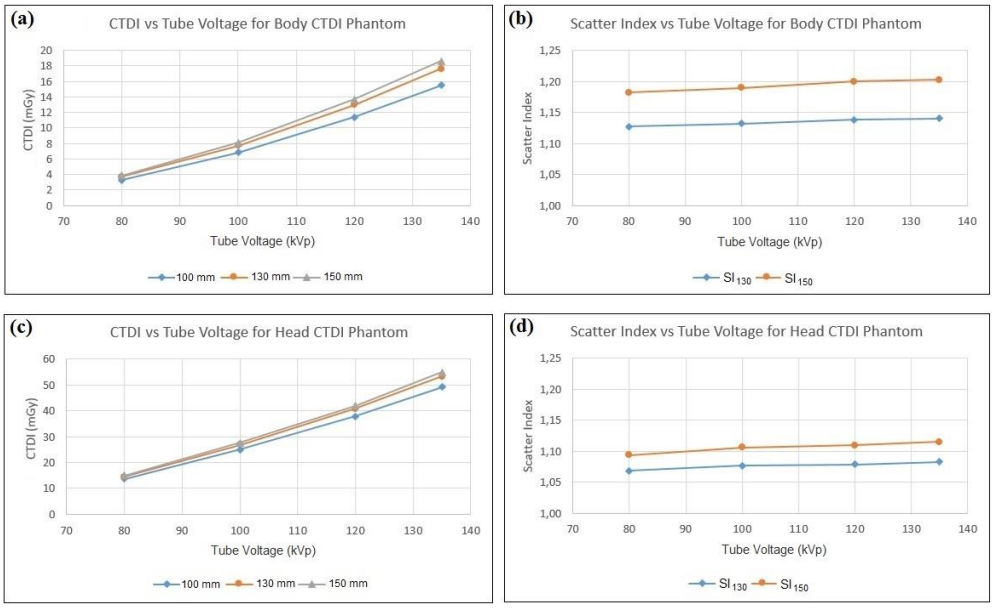

Figure 3. (a) The $CTDI_{100}$, $CTDI_{130}$ and $CTDI_{150}$ curves for the body CTDI phantom, and (b) corresponding SI_{130} and SI_{150}, (c) $CTDI_{100}$, $CTDI_{130}$ and $CTDI_{150}$ curves for the head CTDI phantom, and (d) corresponding SI_{130} and SI_{150}.

whereas for beam widths less than 10 mm the scattering was usually considered very small and negligible. However, a previous study with Monte Carlo simulations had shown that scattering within beam widths less than 10 mm is also significant.[15]

Scatter index is a measure of the scattered radiation and can be used to compare different CT protocols and CT scanners using the same standard CTDI phantom. For the scatter index measurements, we used a variation of tube voltages (80, 100, 120 and 135 kVp), tube currents (25, 50, 100, 120 and 120 mA), and pitches (0.75, 0.875, 1.375 and 1.5).

3. Results and discussion

The $CTDI_{100}$, $CTDI_{130}$ and $CTDI_{150}$ curves for the body CTDI phantom at tube currents 100 mA, pitch 0.875, and tube voltage variation (80-135 kVp) are shown in Figure 3a. The corresponding SI_{130} and SI_{150} are shown in Figure 3b, resulting in SI_{130} and SI_{150} values of 1.13 ± 0.01 and 1.19 ± 0.01. The corresponding $CTDI_{100}$, $CTDI_{130}$ and $CTDI_{150}$ curves for the head CTDI phantom are shown in Figure 3c, and the corresponding SI_{130} and SI_{150} results are 1.08 ± 0.01 and 1.11 ± 0.01. It is clear that both scatter indexes (SI_{130} and SI_{150}) were larger for the body CTDI phantom than for head CTDI phantom. The SI_{150} values were markedly larger than the SI_{130} values, which means that scattering beyond the length of 130 cm is still significant. The SI_{130} and SI_{150} values increase slightly with increasing tube voltage.

The $CTDI_{100}$, $CTDI_{130}$ and $CTDI_{150}$ curves for tube current variation (25-120 mA) at tube voltage 120 kVp, pitch 0.875, for the body CTDI phantom are shown in Figure 4a, with corresponding SI_{130} and SI_{150} of 1.14 ± 0.00 and 1.20 ± 0.00 (Figure 4b). The $CTDI_{100}$, $CTDI_{130}$ and $CTDI_{150}$ curves for tube currents variation for the head CTDI phantom are shown in Figure 4c, with corresponding SI_{130} and SI_{150} of 1.08 ± 0.00 and 1.11 ± 0.00. From the data it is clear that scatter indexes (SI_{130} and SI_{150}) in the body CTDI phantom were consistently larger than that in the head CTDI phantom as previously obtained. It also shows that SI_{150} is significantly larger than SI_{130}. Figure 4 indicates that the SI_{130} and SI_{150} values were independent of tube current.

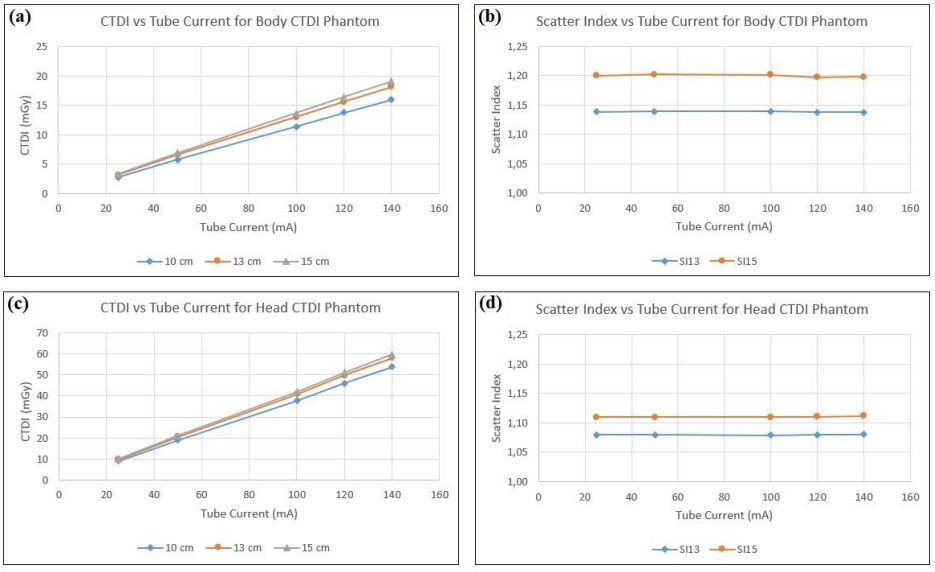

Figure 4. (a) The $CTDI_{100}$, $CTDI_{130}$ and $CTDI_{150}$ curves for tube current variation in the body CTDI phantom, and (b) corresponding SI_{130} and SI_{150} , (c) $CTDI_{100}$, $CTDI_{130}$ and $CTDI_{150}$ curves for tube current variation in head CTDI phantom, and (d) corresponding SI_{130} and SI_{150}.

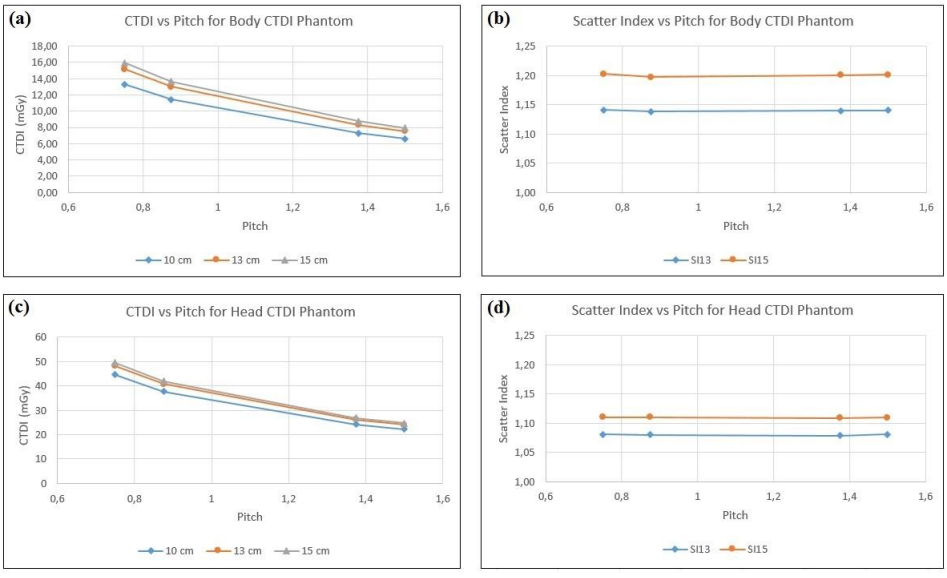

Figure 5. (a)The $CTDI_{100}$, $CTDI_{130}$ and $CTDI_{150}$ curves for pitch variation in the body CTDI phantom, and (b) corresponding SI_{130} and SI_{150} values, (c) $CTDI_{100}$, $CTDI_{130}$ and $CTDI_{150}$ curves for pitch variation in the head CTDI phantom, and (d) corresponding SI_{130} and SI_{150}.

The $CTDI_{100}$, $CTDI_{130}$ and $CTDI_{150}$ curves for pitch variation (0.75-1.5) at tube voltage 120 kVp, tube currents100 mA, and in body CTDI phantom are shown in Figure 5a, with corresponding SI_{130} and SI_{150} values of 1.14 ± 0.00 and 1.20 ± 0.00 (Figure 5b). The $CTDI_{100}$, $CTDI_{130}$ and $CTDI_{150}$ curves for pitch variation in the head CTDI phantom are shown in Figure 5c, with corresponding SI_{130} and SI_{150} of 1.08 ± 0.00 and 1.11 ± 0.00 (Figure 5d). Figure 5 indicates that the SI_{130} and SI_{150} values were independent of pitch variation.

If scattering outside the 100 mm length was non-existent then the SI_{130} value would be 1.00, otherwise it would be greater than 1.00. Our measurements indicate that scattering index value is significant, with SI_{130} values of about 1.14 in the body CTDI phantom and about 1.08 in the head CTDI phantom, using a beam width less than 10 mm. This indicates that the nominal $CTDI_{100}$ value is too small (undervalued) because it ignores scattering beyond the 100 mm boundary. For a beam width larger than 10 mm, the magnitude of this scatter would be even greater.

Scattering index values of SI_{150} were about 1.20 in the body CTDI phantom and about 1.11 in the head CTDI phantom. The value of SI_{150} was greater that SI_{130} by about 0.06 in the body CTDI phantom and by about 0.03 in the head CTDI phantom, indicating that there is still significant scatter radiation in the area between 130 mm and 150 mm. This indicated that SI_{130} does not fully describe the actual scattering dose in standard CTDI phantoms, even for beam widths less than 10 mm. This suggests that the use of SI_{150} is more appropriate for describing the actual scattering dose.

However, the use of a single standard CTDI phantom (either body or head) with a length of 150 mm may not adequately describe the actual scattering dose. A previous study using a series of six CTDI phantoms with a total length of 900 mm resulted a 150 mm dose profile that was significantly different from that using only a single CTDI phantom of 150 mm.[17] Equilibrium doses were obtained if the integration was carried out for about 600 mm. However, these measurements were made for beam widths of 20 mm or more,[17] and the profile difference for beam widths of less than 10 mm are have not been studied. Boone, using Monte Carlo simulation, showed that the underestimation of $CTDI_{100}$ compared with the equilibrium dose was systematic, applying to narrow beam width (less than 10 mm) and wide beams alike, and slowly becomes larger with increasing beam width.[15] Our results indicate that this underestimation also occurs for beam widths below 10 mm.

The scatter index value is strongly influenced by the size of phantom. It is larger for the body CTDI phantom than the head CTDI phantom, because of the larger volume of scattering involved. Increased tube voltage produced a slightly larger scatter index, due to a change in the spectrum and the quality of the x-rays.[23] At higher voltages, the x-ray spectrum becomes slightly wider so that the scattering also increases, but the increase in scattering is not significant.

Changes in the tube current and pitch did not affect the magnitude of the scattering index. The tube current only affects the intensity of the x-ray spectrum, and the scattering does not change. Similarly, although the CTDI value dropped significantly with increases in pitch value,[24] the amount of scattering does not change.

Our study has several limitations. First, the measurements were made on a single CTDI phantom with a length of 150 mm, whose equilibrium dose was unknown, so that the scatter index may be smaller than anticipated. To evaluate the actual scatter index, it would be necessary to measure at least four CTDI phantoms with a total length of at least 600 mm. Second, the measurements were done using only one beam width, i.e. 8 mm. Evaluation for other beam widths needs to be done, since different beam widths are often used in clinical applications. Third, the measurements were done on a particular CT scanner. It is necessary to study other scanners.

4. Conclusion

We found that the scatter index radiation dose of a CT scan beyond the 100 mm limit is significant, so that the standard value of $CTDI_{100}$ is too low since it ignores this scattering radiation. We found that even scatter index 130 does not accommodate all the actual scattering, and scatter index 150 is closer to that required to measure the actual amount of scattering dose. The scatter index values were significantly larger in the body CTDI phantom than in the head CTDI phantom. Increased tube voltages cause slight increases in scatter index but changes in tube current and pitch had no effect on scattering index values.

Acknowledgements

This work was funded by the Research and Innovation Program, Bandung Institute of Technology (ITB), No. 107v/I1.C01/PL/2017.

References

[1] C. Anam, F. Haryanto, R. Widita, I. Arif, and G. Dougherty, "Profile of CT scan output dose in axial and helical modes using convolution," J. Phys. Conf. Ser. **694**(1), 012–034 (2016).

[2] J.M. Boone, "Dose spread functions in computed tomography: A Monte Carlo study," Med. Phys. **36**(10), 4547–4554 (2009).

[3] S. Mori, M. Endo, T. Tsunoo, S. Kandatsu, S. Tanada, H. Aradate, Y. Saito, H. Miyazaki, K. Satoh, S. Matsushita, and M. Kusakabe, "Physical performance evaluation of a 256-slice CT-scanner for four-dimensional imaging," Med. Phys. **31**(6), 1348–1356 (2004).

[4] C. Anam, F. Haryanto, R. Widita, I. Arif, and G. Dougherty, "Automated calculation of water equivalent diameter (D_W) based on AAPM task group 220," J. Appl. Clin. Med. Phys. **17**(4), 320–333 (2016).

[5] J.A. Bauhs, T.J. Vrieze, A.N. Primak, M.R. Bruesewitz, and C.H. McCollough, "CT dosimetry: comparison of measurement techniques and devices," RadioGraphics. **28**(1), 245–253 (2008).

[6] American Association of Physicists in Medicine, "The measurement, reporting, and management of radiation dose in CT. Report of AAPM TG of the Diagnostic Imaging Council CT Committee No. 23," AAPM Report No. **96**; (2008).

[7] McNitt-Gray F, "AAPM/RSNA physics tutorial for residents: topics in CT-radiation dose in CT. RadioGraphics. **22**(6), 1541–53 (2002).

[8] L.W. Goldman, "Principles of CT: radiation dose and image quality," J. Nucl. Med. Technol. **35**(4), 213–25. (2007).

[9] T.B. Shope, R.M. Gagne, and G.C. Johnson, "A method for describing the doses delivered by transmission x-ray computed tomography," Med. Phys. **8**(4), 488–95 (1981).

[10] L.W. Goldman, "Principles of CT; Multislice CT," J. Nucl. Med. Technol. **36**(2):57–68 (2008).

[11] C.H. McCollough, F.E. Zink, "Performance evaluation of a multi-slice CT system," Med Phys. **26**(11), 2223–2230 (1999).

[12] J. Geleijns, A.M. Salvado, P.W. deBruin, R. Mather, Y. Muramatsu, and M.F. McNitt-Gray, "Computed tomography dose assessment for a 160 mm wide, 320 detector row, cone beam scanner," Phys. Med. Biol. **54**(10), 3141–3159 (2009).

[13] S. Kim, H. Song, E. Samei, F. Yin, T.T. Yoshizumi, "Computed tomography dose index and do.se length product for cone-beam CT: monte carlo simulations of a commercial system," J. Appl. Clin. Med. Phys. **12**(2), 84–95 (2010).

[14] R.L. Dixon, "A new look at CT dose measurement: Beyond CTDI," Med. Phys. **30**(6), 1272–1280 (2003).

[15] J.M. Boone, "The trouble with CTDI100," Med. Phys. **34**(4), 1364–1371 (2007).

[16] C. Ruan, E.G. Yukihara, W.J. Clouse, B.R. Patricia, P.B.R. Gasparian, and S. Ahmad, "Determination of multislice computed tomography dose index (CTDI) using optically stimulated luminescence technology." Med. Phys. **37**(7), 3560–3568 (2010).

[17] S. Mori, M. Endo, K. Nishizawa, T. Tsunoo, Aoyama, H. Fujiwara, and K. Murase, "Enlarged longitudinal dose profiles in cone-beam CT and the need for modified dosimetry," Med. Phys. **32**(4), 1061–1069 (2005).

[18] IAEA, "Status of computed tomography: Dosimetry for wide cone beam scanners," IAEA-Human Health Reports No. 5, (2011).

[19] K. Matsubara, "Computed tomography dosimetry: From basic to state-of-the-art techniques," Med. Phys. Int. **5**(1), 61–67 (2017).

[20] B. Cederquist, "Evaluation of two thin CT dose profile detectors and a new way to perform QA in a CTDI head phantom," Master Degree Thesis in Radiation Physics. Göteborg University, Göteborg, Sweden (2008).

[21] A. Palm, E. Nilsson, and L. Herrnsdorf, "Absorbed dose and dose rate using the Varian OBI 1.3 and 1.4 CBCT system," J. Appl. Clin. Med. Phys. **11**(1), 229–240 (2010).

[22] RTI Electronics, "CT dose profile analyzer manual version 4.0B," RTI Electronics, Sweden (2009).

[23] J.M. Boone, and J.A. Seibert, "An accurate method for computer-generating tungsten anode x-ray spectra from 30 to 140 kV," Med. Phys. **24**(11), 1661–1670 (1997).

[24] G. Wang, and M.W. Vannier, "The effect of pitch in multislice spiral/helical CT," Med. Phys. **26**(12), 2648–2653. (1999).