A size-specific effective dose for patients undergoing CT examinations

by Choirul Anam

PAPER · OPEN ACCESS

A size-specific effective dose for patients undergoing CT examinations

View the article online for updates and enhancements.

A size-specific effective dose for patients undergoing CT examinations

C Anam[1], F Haryanto[2], R Widita[2], I Arif[2], T Fujibuchi[3] and G Dougherty[4]

[1] Department of Physics, Faculty of Mathematics and Natural Sciences, Diponegoro University, Indonesia.
[2] Department of Physics, Faculty of Mathematics and Natural Sciences, Bandung Institute of Technology, Indonesia.
[3] Department of Health Sciences, Faculty of Medical Sciences, Kyushu University, 3-1-1 Maidashi, Higashi-ku, Fukuoka, Japan.
[4] Applied Physics and Medical Imaging, California State University Channel Islands, California, USA.

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

Abstract. This study aims to develop a simple method for estimating the size-specific effective dose using the ImPACT software. The size-specific effective dose was calculated from the images of patients who underwent CT examinations of the thorax and abdomen regions. Volume computed tomography dose index ($CTDI_{vol}$) and mAs data were obtained from the dose report. The average of mAs and $CTDI_{vol}$ were used to determine the normalized $CTDI_{vol}$ ($nCTDI_{vol}$). Patient size was expressed in effective diameter (D_{eff}), and was measured at nine slices along the z-axis. The normalized size-specific dose estimate (nSSDE) was then calculated. The normalized size-specific effective dose was obtained in the "effective dose" text-box by inputting an arbitrary value in the "CTDI (air)" text-box so that the "$CTDI_{vol}$" text-box showed a similar value to the nSSDE. The results show that the normalized size-specific effective dose decreases exponentially with increasing patient size. The results are consistent with results of Sahbaee formula to within 20%.

1. Introduction

There are several dosimetric quantities in CT scanning, including volume computed tomography dose index ($CTDI_{vol}$) [1, 2], dose-length product (DLP) [3, 4], size-specific dose estimate (SSDE) [5, 6], organ dose [7, 8], and effective dose (E) [9]. Among them, the effective dose is considered as the best quantity to relate cancer risk to X-ray radiation from CT [10]. It is known that cancer risk is influenced not only by the magnitude of the average patient dose or organ dose, but is also determined by the sensitivity of each exposed organ to the radiation [11]. With this effective dose, the magnitude of CT dose can be compared to other radiological modalities, such as fluoroscopy, mammography, dental radiology, and conventional radiology [12], and it can also be compared with the natural radiation dose [13].

Up to now, there were several techniques for calculating the effective dose. One way was by using a software package such as ImPACT [14], CT-Expo [15] or Waza-ari [16], another was by measurement using an anthropomorphic phantom and a small detector such as photoluminescence dosemeter (PLD) [17], or by calculation using Monte Carlo simulation [18], or it could be estimated from DLP using a conversion value of DLP/E or the so-called *k*-factor [19]. However, all of these approaches are still limited to a phantom of a standard size, so the results may differ from an actual patient.

Several investigators have reported that estimates of patient dose, organ dose, and effective dose using output CT machine only is not sufficient, and that the size of the patient should be taken into account [20-23]. This study introduced a simple method for estimating the size-specific effective dose using ImPACT.

2. Method

2.1. Overall steps of this study

The overall steps in this study are shown in Figure 1. The size-specific effective dose was calculated from patients who underwent thoracic and abdominal CT examinations. The effective diameter (D_{eff}) was determined from the image of the patient. $CTDI_{vol}$ and mAs values were derived from the dose report. From the average of the mAs and $CTDI_{vol}$ values, the normalized $CTDI_{vol}$ (in units of mGy /100 mAs) and normalized effective dose (nSSDE, taking into account the patient's size) were determined. Finally, based on this nSSDE value, the normalized size-specific effective dose was calculated using ImPACT software. The results obtained in this approach were compared with the results calculated by the Sahbaee formula [21].
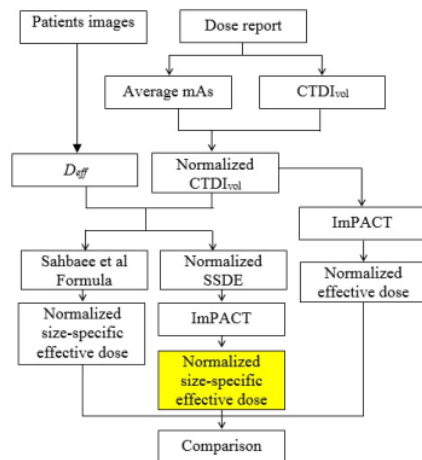

Figure 1. Overall steps in this study.

2.2. Patient Images

We calculated the size-specific effective dose from 24 patients who underwent thoracic CT examination and 27 patients who underwent abdominal CT examinations. The age averages were 57.8 (± 13.8) and 48.7 (± 14.1) years for the patients underwent thoracic and abdominal examinations respectively. All patients were scanned using a MDCT Siemens Somatom 6. Scan parameters were shown in Table 1. The MDCT was equipped with tube current modulation (TCM) with 70 mAs reference for thoracic examinations and 95 mAs for abdominal examinations.

Table 1. Scan parameters of CT examinations in this study.

Scanning parameter	Values
Tube voltage	130 kVp
Rotation time	0.6 s
Pitch	0.8
Slice thickness	2 mm

2.3. D_{eff} calculation

In this study, the patient size was characterized by the effective diameter (D_{eff}) [24]. The D_{eff} of each patient was calculated from images of the patient at nine slices (locations) along the z-axis [5] as shown in Figure 2(a). The maximum diameters in the lateral (D_{LAT}) and antero-posterior (D_{AP}) directions were determined, as shown in Figure 2(b). The value of D_{eff} was calculated from:

$$D_{eff} = \sqrt{D_{AP} \times D_{LAT}} \tag{1}$$

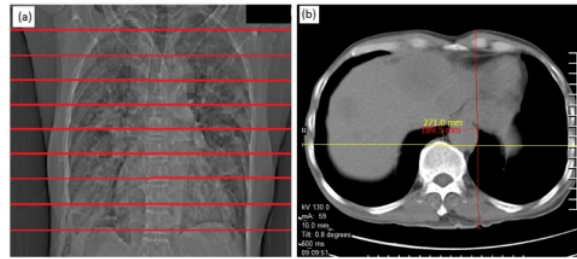The average of D_{eff} was then calculated from these nine values of D_{eff}.

Figure 2. (a) Nine slices along the z-axis for determining D_{eff} for every patient. (b) D_{eff} for each slice was determined by the square root of the product of the maximum diameters in the lateral direction (D_{LAT}) and in the antero-posterior direction (D_{AP}).

2.4. $nCTDI_{vol}$ and nSSDE

$CTDI_{vol}$ and mAs values were taken from the CT scanner dose report. The mAs value is the product of tube current and rotation time. In the tube current modulation (TCM) technique, the tube current is not constant throughout the scan process, so that the average mAs should be calculated. The normalized $CTDI_{vol}$ ($nCTDI_{vol}$) was calculated in units of mGy/100 mAs [5]. The quantity used for describing patient dose is the size-specific dose estimate (SSDE). Normalized SSDE (nSSDE) was calculated by the equation:

$$nSSDE = nCTDI_{vol} \times a \times e^{-b \times D_{eff}} \tag{2}$$

where a is 3.704369 and b is 0.03671937 for thoracic and abdominal examinations [25].

2.5. ImPACT and scan protocol

ImPACT is software developed by Im-PACT group (UK National Health Service CT Evaluation Centre, London, UK) which can be used to estimate organ doses and effective doses for many scanners with different examination parameters [12]. In this study, we used ImPACT 1.0.1a (Figure 3). The input of "scan region" for the thoracic and abdominal examination was "body", and the "scan range" inputs are shown in Table 2. Selection of the scan range refers to the protocol and a previous study by Sahbaee [21]. In addition, the effective dose is greatly influenced by the organ weighting factors. In this study we used the ICRP 103 data.

All acquisition parameters, such as spiral pitch and collimation, were inserted into the ImPACT software. The product of tube current and rotation time was set to be 100 mAs. The "CTDI (air)" was filled by trial and error, resulting in expected $nCTDI_{vol}$ (equal to the value of the $nCTDI_{vol}$ as in the dose report). It should be noted that this effective dose does not take patient size into consideration. The "CTDI (air)" text-box was filled again by trial and error with a value such that the "$CTDI_{vol}$" box showed the nSSDE value. The effective dose value shown was the normalized size-specific effective dose.
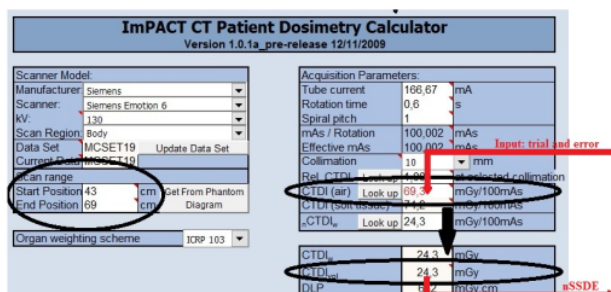
Figure 3. Screen capture of ImPACT software for calculating normalized effective dose and normalized size-specific effective dose. The text box of "CTDI (air)" was filled by trial and error, so that the "CTDI$_{vol}$" box indicated the value of nSSDE.

Table 2. Standard head and body CT examinations [19].

Examination	Start and End z coordinates (cm)	Scan Length (cm)	Scan Coverage
Thorax	43 and 69	26	Start from 1 cm above the lung down to 1 cm below the lung base
Abdomen	20 and 44	24	Start from 1 cm above the superior liver down to 1 cm below the superior iliac crest

2.6. Sahbaee formula

The result of this calculation was compared with the calculated results using the Sahbaee formula [21]. The formula is a patient-based estimation of effective dose for adult protocols across 13 categories, including thoracic and abdominal protocols. It was derived using a validated Monte Carlo program on 58 adult cardiac-torso extended computational phantoms. The correlation between the normalized effective dose (E) and patient size inside the scan coverage is described by an exponential fit:

$$E(D_{eff, avg}) = DLP \times e^{(\alpha \times D_{eff, avg} + \beta)} \tag{3}$$

The α values are -0.04 and -0.05 and the β values are -2.52 and -2.49, for thorax and abdomen respectively [21].

3. Results

3.1. CTDI$_{vol}$ and nCTDI$_{vol}$

The patient size was characterized by the average D_{eff} from nine points along the z-axis. The average D_{eff} for the thoracic examinations was 22.4 (± 2.4) cm; and for the abdominal examinations was 23.5 (±2.0) cm. The average D_{eff} of our patients was lower by about 30% for thorax and 28% for abdomen than the size of the standard 32-cm phantom.

The correlations between CTDI$_{vol}$ and D_{eff} for thoracic and abdominal examinations are shown in Figure 4. The value of CTDI$_{vol}$ increased linearly with D_{eff}, because the average tube current increases with D_{eff}. The average CTDI$_{vol}$ was 4.5 (± 1.2) mGy for thoracic examinations, and the average CTDI$_{vol}$ was 5.1 (± 1.1) mGy for abdominal examinations. The CTDI$_{vol}$ value was 3.5 mGy for D_{eff} about 20 cm, and 7.0 mGy (2-fold increase) for D_{eff} about 28 cm. R^2 values were 0.514 and 0.728 for the thoracic and abdominal examinations respectively.

After normalization, $CTDI_{vol}$ was independent of D_{eff}. The $nCTDI_{vol}$ was constant at about 12 mGy/100 mAs (11.6 ± 0.2 mGy/100 mAs for thoracic examinations and 11.8 ± 0.4 mGy/100 mAs for abdominal examinations). The correlation between nSSDE and D_{eff} for thoracic and abdominal examinations are shown in Figure 4. The nSSDE decreases exponentially with increasing D_{eff}. The average nSSDE values were 18.9 mGy/100 mAs (±1.7 mGy/100 mAs) and 18.7 mGy/100 mAs (±1.7 mGy / 100 mAs). The nSSDE was found to overestimate $nCTDI_{vol}$ by about 63% and 59% for thoracic and abdominal examinations respectively.
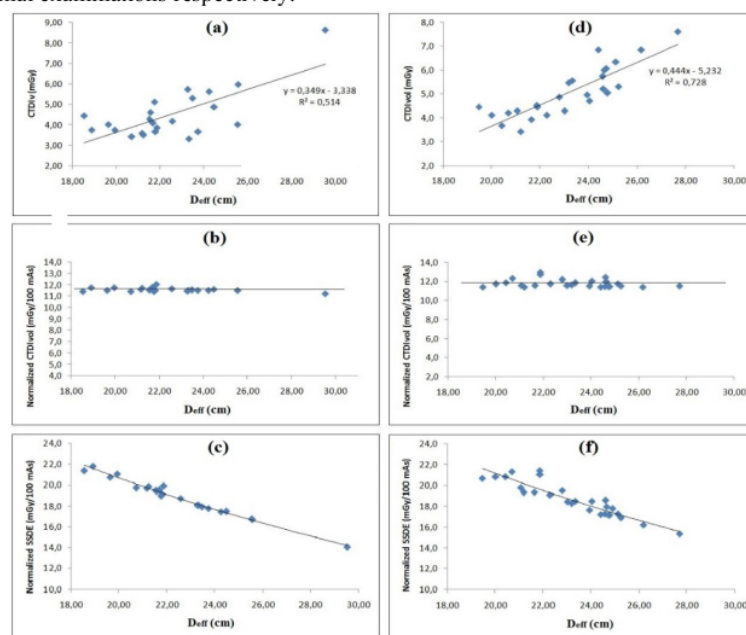

Figure 4. The correlations between $CTDI_{vol}$ and D_{eff}, $nCTDI_{vol}$ and D_{eff}, and nSSDE and D_{eff} for thoracic (a-c) and abdominal examinations (d-f).

3.2. Effective Dose
The normalized standard effective dose and normalized size-specific effective doses for thoracic and abdominal are shown in Figure 5. The standard normalized effective dose calculated using ImPACT is independent of D_{eff}. It was constant at about 6 mSv/100 mA (6.3 ± 0.1 mSv/100 mAs and 5.6 ± 0.2 mSv/100 mAs, for thoracic and abdominal examinations respectively). However the normalized size-specific effective dose decreases exponentially with increasing D_{eff}. For the largest patients in the thoracic examinations, the normalized size-specific effective dose was found to be about 56% higher than for smallest patients; and in the abdominal examinations, the normalized size-specific effective dose was found to be 39% higher than that for smallest patients. The average of the normalized size-specific effective doses were 10.4 (± 1.0) mSv /100 mAs and 8.8 (± 0.8) mSv/100 mAs for thoracic and abdominal examinations respectively.

The same pattern was obtained by using the Sahbaee formula [21]. The differences between our approach and the Sahbaee formula were 4.5 ± 2.5% for the thoracic examinations and 19.5 ± 3.4% for the abdominal examinations. As comparison, the differences between the normalized size-specific effective dose using the Sahbaee formula and the standard normalized standard effective dose using ImPACT (which neglects patient size) were 35.7 ± 6.4% and 23.7 ± 7.6% for thoracic and abdominal examinations respectively.
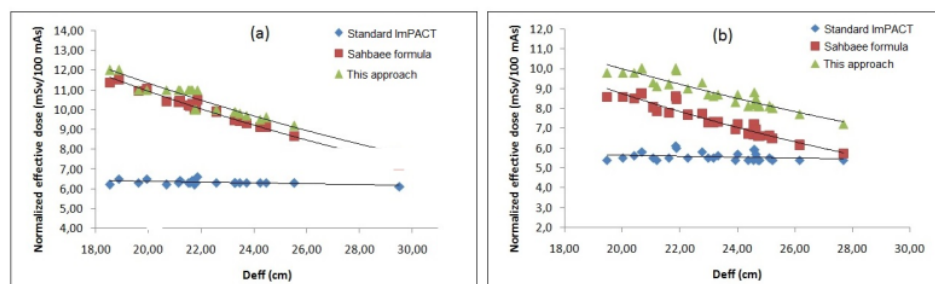
Figure 5. The normalized standard effective dose and normalized size-specific effective doses for (a) thoracic examinations and (b) abdominal examinations.

4. Discussion

Effective dose is a descriptor that reflects the cancer risk of CT examinations. Several previous studies reported that the effective dose can be estimated from the DLP by applying a k-factor [11,19]. The k-factor values has been expanded to take into account age and gender. However, it is still limited to a phantom which may differ from the actual size of patient. By ignoring the size of the patient, effective dose can vary by 100% or more [11]. The k-factor has now been reported for various sizes and for some specific protocols [21], based on validated Monte Carlo simulations on mathematical model phantoms. In addition to using the DLP and k-factor, the simplest method for calculating the effective dose is to use a specific calculator such as ImPACT. However, ImPACT uses a standard phantom representing the standard patient size. This study has attempted to develop a technique for calculating size-specific effective dose using ImPACT, without having to change the ImPACT software itself.

The results showed that the normalized size-specific effective dose decreases exponentially with increasing D_{eff}. The adult patients evaluated in this study with D_{eff} values from 18.5 cm to 29.5 cm, the differences between the largest and smallest normalized size-specific effective dose were about 55% and 40% for thoracic and abdominal examinations respectively. The largest of the normalized size-specific effective dose compared to the normalized standard effective dose (not taking into account D_{eff}) were 90% and 80% for thoracic and abdominal examinations respectively. For pediatric patients with D_{eff} under 15 cm, the differences may be more 100%. Therefore in order to achieve accurate estimates of effective dose, it is critical to take into account the size of the patient.

The results of this approach were consistent with Sahbaee formula [21]. The differences between both were quite small, which are about 5% and 20% for thoracic and abdominal examinations. The discrepancies are possibly due to: First, the values of scan length used in this approach was constant (i.e., 26 cm and 24 cm for thoracic and abdominal examinations), while Sahbaee formula was obtained using many mathematical phantoms with varying size and length. Second, the Sahbaee formula was obtained from GE Light-Speed VCT system and this approach was used to calculate the effective dose from Siemens Somatom-6 CT system. However, the relatively small differences indicated that the size-specific effective dose can be accurately estimated by this approach using the ImPACT software. One advantage of using this software rather than using k-factor and DLP, is that the size-specific effective dose can be estimated for different protocols and scan ranges.

5. Conclusions

The normalized size-specific effective dose has been calculated using ImPACT software, by replacing $nCTDI_{vol}$ with nSSDE. The results show that the normalized size-specific effective dose decreases exponentially with increasing patient size. The results of normalized size-specific effective dose were consistent to within 20% with a Sahbaee formula.

References
[1]   Shope T B, Gagne R M, and Johnson G C 1981 A method for describing the doses delivered by transmission x-ray computed tomography *Med. Phys.* **8** 488–495
[2]   Anam C, Haryanto F, Widita R, Arif I and Dougherty G 2016 Profile of CT scan output dose in axial and helical modes using convolution *J. Phys. Conf. Ser.* **694** 012034
[3]   McNitt-Gray M F 2002 AAPM/RSNA physics tutorial for residents: topics in CT—radiation dose in CT *RadioGraphic.* **22** 1541–1553
[4]   Huda W and Mettler F A 2011 Volume CT dose index and dose-length product displayed during CT: What good are they? *Radiology* **258** 236-242
[5]   Anam C, Haryanto F, Widita R, Arif I and Dougherty G 2016 Automated calculation of water equivalent diameter (D_W) based on AAPM task group 220 *J. Appl. Clin. Med. Phys.* **17** 320-333
[6]   Anam C, Haryanto F, Widita R, Arif I and Dougherty G 2016 A Fully automated calculation of size-specific dose estimates (SSDE) in thoracic and head CT examinations *J. Phys. Conf. Ser.* **694** 012030
[7]   Zhang D, Li X, Gao Y, Xu G, and Liu B 2013 A method to acquire CT organ dose map using OSL dosimeters and ATOM anthropomorphic phantoms *Med. Phys.* **40** 081918
[8]   Anam C, Haryanto F, Widita R, Arif I, Dougherty G, and McLean D 2016 Estimation of eye radiation dose during nasopharyngeal CT examination for an individual patient *Information (Japan)* **19** 3951-3962
[9]   Zhang Y, Li X, Segars P, and Samei E 2012 Organ doses, effective doses, and risk indices in adult CT: Comparison of four types of reference phantoms across different examination protocols *Med. Phys.* **39** 3404-3423
[10]   Kalender W A 2014 Dose in x-ray computed tomography *Phys. Med. Biol.* **59** R129–R150
[11]   McCollough C H, Christner J A, and Kofler J M 2010 How effective is effective dose as a predictor of radiation risk? *Am. J. Roentgenol.* **194** 890–896
[12]   Huda W, Sterzik A, Tipnis S, and Schoepf U J 2010 Organ doses to adult patients for chest CT. *Med. Phys.* **37** 842-847
[13]   Bauhs J A, Vrieze T J, Primak A N, Bruesewitz M R and McCollough C H 2008 CT dosimetry: comparison of measurement techniques and devices *RadioGraphics* **28** 245-253
[14]   Brady Z, Cain T M, and Johnston P N 2012 Comparison of organ dosimetry methods and effective dose calculation methods for paediatric CT *Australas Phys Eng Sci Med* **35** 117–134
[15]   Brix G, Lechel U, Veit R, Truckenbrodt R, Stamm G, Coppenrath E M, Griebel J, Nagel H D 2004 Assessment of a theoretical formalism for dose estimation in CT: an anthropomorphic phantom study *Eur. Radiol.* **14** 1275–1284
[16]   Ban N, Takahashi F, Sato K, Endo A, Ono K, Hasegawa T, Yoshitake T, Katsunuma Y, and Kai M 2011 Development of a web-based CT dose calculator: WAZA-ARI *Radiat. Prot. Dosimetry.* **147** 333–337
[17]   Fujibuchi T, Funabashi N, Hashimoto M, Kato H, Kurokawa M, Deloar H M, Kunieda E, Komuro I, and Sakae T 2010 Estimate of organ radiation absorbed doses in clinical CT using the radiation tratment planning system *Radiat. Prot. Dosimetry.* **142** 174–183
[18]   DeMarco J J, Cagnon C H, Cody D D, Stevens D M, McCollough C H , Zankl M, Angel E, and McNitt-Gray M F 2007 Estimating radiation doses from multidetector CT using Monte Carlo simulations: effects of different size voxelized patient models on magnitudes of organ and effective dose *Phys. Med. Biol.* **52** 2583–2597

[19] Huda W, Ogden K M, Khorasani M R 2008 Converting dose-length product to effective dose at CT *Radiology* **248** 995-1003

[20] Turner A C, Zhang D, Khatonabadi M, Zankl M, DeMarco J J, Cagnon C H, Cody D D, Stevens D M, McCollough C H, and McNitt-Gray M F 2011 The feasibility of patient size-corrected, scanner-independent organ dose estimates for abdominal CT exams *Med. Phys.* **38** 820-829

[21] Sahbaee P, Segars W P, and Samei E 2014 Patient-based estimation of organ dose for a population of 58 adult patients across 13 protocol categories *Med. Phys.* **47** 072104

[22] Anam C, Haryanto F, Widita R, Arif I, and Dougherty G 2017 The size-specific dose estimate (SSDE) for truncated computed tomography images *Radiat. Prot. Dosim.* **175** 313-320

[23] Anam C, Fujibuchi T, Toyoda T, Sato N, Haryanto F, Widita R, Arif I, and Dougherty G 2018 A simple method for calibrating pixel values of the CT localizer radiograph for calculating water-equivalent diameter and size-specific dose estimate *Radiat. Prot. Dosim.* **179** 158-168

[24] Anam C, Haryanto F, Widita R, Arif I, and Dougherty G 2017 The evaluation of the effective diameter (D_{eff}) calculation and its impact on the size-specific dose estimate (SSDE) *Atom Indonesia* **43** 55-60

[25] AAPM 2011 *Size-specific Dose Estimates (SSDE) in Pediatric and Adult Body CT Examinations* (College Park: AAPM)

A size-specific effective dose for patients undergoing CT examinations

SPECIFIC DOSE ESTIMATE (SSDE) FOR TRUNCATED COMPUTED TOMOGRAPHY IMAGES", Radiation Protection Dosimetry, 2017
Publication

10   A Amer, T Marchant, J Sykes, J Czajka, C Moore. "Imaging doses from the Elekta Synergy X-ray cone beam CT system", The British Journal of Radiology, 2007
Publication   <1%

11   Susan D. Kost, Nicholas D. Fraser, Diana E. Carver, David R. Pickens et al. "Patient-specific dose calculations for pediatric CT of the chest, abdomen and pelvis", Pediatric Radiology, 2015
Publication   <1%

12   mafiadoc.com
Internet Source   <1%

13   Medical Radiology, 2012.
Publication   <1%

14   Pooyan Sahbaee, W. Paul Segars, Ehsan Samei. "Patient-based estimation of organ dose for a population of 58 adult patients across 13 protocol categories", Medical Physics, 2014
Publication   <1%

15 Erin Angel. "Monte Carlo simulations to assess the effects of tube current modulation on breast dose for multidetector CT", Physics in Medicine and Biology, 02/07/2009
Publication

<1 %

16 H Schlattl. "Dose conversion coefficients for CT examinations of adults with automatic tube current modulation", Physics in Medicine and Biology, 10/21/2010
Publication

<1 %

17 Walter Huda. "Computing effective doses to pediatric patients undergoing body CT examinations", Pediatric Radiology, 04/2008
Publication

<1 %

18 docplayer.net
Internet Source

<1 %

19 docserv.uni-duesseldorf.de
Internet Source

<1 %

20 Jan Juszczyk, Pawel Badura, Joanna Czajkowska, Agata Wijata et al. "Automated size-specific dose estimates using deep learning image processing", Medical Image Analysis, 2021
Publication

<1 %

21 Kent J. Gregory, Giovanni Bibbo, John E. Pattison. "On the uncertainties in effective

<1 %

dose estimates of adult CT head scans",
Medical Physics, 2008
Publication

22   static.healthcare.siemens.com   <1%
      Internet Source

23   Federica Zanca, Martine Demeter, Raymond   <1%
      Oyen, Hilde Bosmans. "Excess radiation and
      organ dose in chest and abdominal CT due to
      CT acquisition beyond expected anatomical
      boundaries", European Radiology, 2011
      Publication

24   Kazuki Kuriyama, Kosuke Matsubara, Shu   <1%
      Hisahara, Yukie Nagata et al. "Effect of table
      height displacement and patient center
      deviation on size-specific dose estimates
      calculated from computed tomography
      localizer radiographs", Physical and
      Engineering Sciences in Medicine, 2020
      Publication

25   Tian, Xiaoyu, Xiang Li, W. Paul Segars, Donald   <1%
      P. Frush, Ehsan Samei, Robert M. Nishikawa,
      and Bruce R. Whiting. "Patient- and cohort-
      specific dose and risk estimation for
      abdominopelvic CT: a study based on 100
      patients", Medical Imaging 2012 Physics of
      Medical Imaging, 2012.
      Publication

26 Xiang Li, Ehsan Samei, Cameron H. Williams, W. Paul Segars et al. "Effects of protocol and obesity on dose conversion factors in adult body CT", Medical Physics, 2012
Publication

<1%

27 Xiang Li, Ehsan Samei, W. Paul Segars, Gregory M. Sturgeon, James G. Colsher, Donald P. Frush. "Patient-specific dose estimation for pediatric chest CT", Medical Physics, 2008
Publication

<1%

28 biblio.ugent.be
Internet Source

<1%

29 www.medikalfizik.org
Internet Source

<1%

30 www.tandfonline.com
Internet Source

<1%

31 Akmal Sabarudin, Zakira Mustafa, Khadijah Mohd Nassir, Hamzaini Abdul Hamid, Zhonghua Sun. "Radiation dose reduction in thoracic and abdomen-pelvic CT using tube current modulation: a phantom study", Journal of Applied Clinical Medical Physics, 2015
Publication

<1%

32 Cosimo Nardi, Sergio Salerno, Roberto Molteni, Mariaelena Occhipinti et al.

<1%

"Radiation dose in non-dental cone beam CT applications: a systematic review", La radiologia medica, 2018

Publication

Exclude quotes	Off	Exclude matches	Off
Exclude bibliography	On		