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Effective Dose and Size Specific Dose Estimation with and without Tube Current Modulation for Thoracic Computed Tomography Examinations: A Phantom Study

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Abstract**—**The purpose of this study is to reduce radiation dose for chest CT examination by including Tube Current Modulation (TCM) to a standard CT protocol. A scan of an anthropomorphic male Alderson phantom was performed on a 128-slice scanner. The estimation of effective dose (ED) in both scans with and without mAs modulation was done via multiplication of Dose Length Product (DLP) to a conversion factor. Results were compared to those measured with a CT-Expo software. The size specific dose estimation (SSDE) values were obtained by multiplication of the volume CT dose index (CTDIvol) with a conversion size factor related to the phantom's effective diameter. Objective assessment of image quality was performed with Signal to Noise Ratio (SNR) measurements in phantom. SPSS software was used for data analysis. Results showed including CARE Dose 4D; ED was lowered by 48.35% and 51.51% using DLP and CT-expo, respectively. In addition, ED ranges between 7.01 mSv and 6.6 mSv in case of standard protocol, while it ranges between 3.62 mSv and 3.2 mSv with TCM. Similar results are found for SSDE; dose was higher without TCM of 16.25 mGy and was lower by 48.8% including TCM. The SNR values calculated were significantly different ($p=0.03<0.05$). The highest one is measured on images acquired with TCM and reconstructed with Filtered back projection (FBP). In conclusion, this study proves the potential of TCM technique in SSDE and ED reduction and in conserving image quality with high diagnostic reference level for thoracic CT examinations.

Keywords**—**Anthropomorphic phantom, computed tomography, CT-expo, radiation dose.

I. Introduction

SINCE the introduction of computed tomography (CT) in the 1970s, the number of CT examinations has increased significantly. The CT imaging modality has become an essential examination in diagnostic radiology. While the clinical value and benefits of CT are unquestionable, it is increasingly reported that there could be potentially harmful effects on patients due to radiation exposure from these examinations. In order to minimize the health risks involved with the radiation exposure in CT scans, continuous efforts are being made to improve the technology for achieving reduction in the total dose received by the patient undergoing CT diagnosis [1], [2]. In addition, various approaches for dose reduction have been developed [3]. TCM is one of these strategies, which allows current to be adjusted automatically with scanning object thickness [4]. Several studies based on phantom used different protocols for dose reduction as low as reasonably achievable [5], [6].

In radiology, as an indicator of radiation dose, ED is the only parameter to evaluate risk caused by exposure radiations measured in milli-Sieverts (mSv) [7]. Therefore, ED is not used for individual measurements. However, it can be used for comparison and optimization of protocols used in medical radiation applications. Another important actual indicator of dose estimation in CT is the SSDE which depends on both patient size and the anatomy within the scanned volume. Currently, CTDIvol, a dose index reflecting scanner output, is available on most commercial scanners. However, CTDIvol alone is not sufficient for estimating patient dose because under the same scanning conditions, dose to a patient is determined by the total absorption of x-ray photons. To address this limitation of CTDIvol, the American Association of Physicists in Medicine recently published a report on SSDE in body CT, where a conversion factor depending on patient's size is used to calculate an estimate of patient dose from CTDIvol [8].

In this study, it was aimed at evaluating the effect of including TCM in SSDE and ED reduction beside image quality performance.

II. Materials and Methods

A. Phantom Study

This experimental study was performed on an anthropomorphic adult male Alderson Rando phantom as shown in Fig. 1. This phantom is made of tissue equivalent materials that simulate the radiation attenuation characteristics of an adult of weight 73.5 kg and height 175 cm. In our study, we used thoracic slabs numbered from slice 9 to slice 23.

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Fig. 1 Photograph of the RANDOs anthropomorphic phantom in the Siemens Definition Edge 128-slice CT scanner

B. Scanning Techniques

During CT acquisitions, the phantom was centered as in routine clinical thoracic CT examinations. The CT exam performed on a 128-slice CT system (SOMATOM Definition Edge, Siemens Healthcare, Forchheim, Germany) using two protocols; a standard protocol and a modified protocol with CARE Dose4D. The scout of phantom such as lateral and anterior posterior was performed for scan guidance and later effective diameter calculation. The scan was followed by helical acquisition. All exposure parameters (kVp and mAs) were manually adjusted based on phantom size as tabulated in Table I.

TABLE I
ACQUISITION PARAMETERS FOR THORACIC CT EXAMINATION WITH AND WITHOUT TCM

Parameters	Without TCM	With TCM
Slice thickness (mm)	1	1
Tube potential(kVp)	120	120
Ref mAs	200	200
Slice collimation	0.6*128	0.6*128
Length acquisition (mm)	344	344
Pitch	1.05	1.05
Dose modulation	off	On
Kernel	B30f medium smooth	J30f medium smooth

C. CT-Expo Study

CT-Expo V.4 is a recent MS Excel application written in Visual Basic programming. This software provides automatic calculation of CTDIw, CTDIvol, DLP values, and ED according to ICRP-60 and ICRP-103 guidelines for four anthropomorphic mathematical phantoms (see Fig. 2); namely, ADAM, EVA, CHILD, and BABY [9] by specifying the scanner model, scanner manufacturer, and scanning parameters as inputs. The scan parameters of interest are the tube voltage (kV), tube current (mA), acquisition time (s) or alternatively the current time product (mAs), the total collimation (mm), the table feed (mm), the reconstructed slice thickness (mm), and the number of scan series.

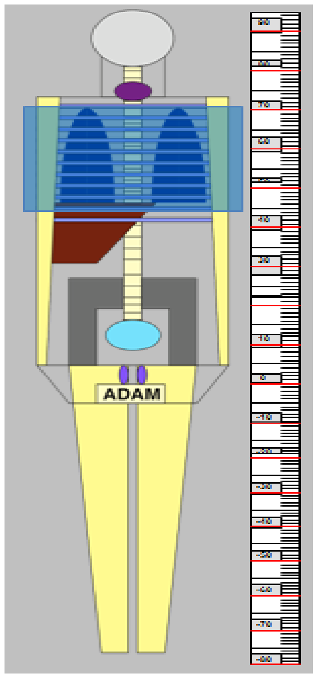

Fig. 2 Mathematical phantom from CTEXPO, show the range of scanning during CT thoracic examinations [9]

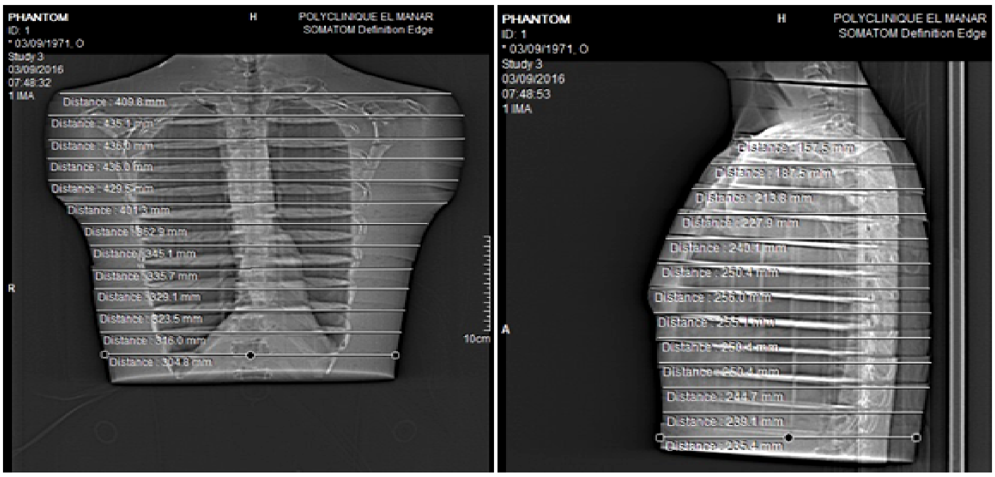

Fig. 3 Phantom effective diameter calculation

D. Radiation Dose

ED for each protocol was estimated by using two methods: the typical method based on the DLP using the universal k-factor, which depends on the anatomic region examined where CT thorax for an adult is 0.014 mSv/mGy cm [7], and a second method based on the computational phantom measurement by CT-Expo (Version 2.4, Germany).

In the case of SSDE, phantom size was estimated based on the geometrical parameters of the phantom cross section, such as lateral and anterior-posterior dimension. Anterior-posterior (AP) and lateral (Lat) diameters were measured on transverse CT images. AP and Lat diameter were measured from the lateral localizer radiograph and the frontal localizer radiograph respectively at every 2.5 cm interval (along the z axis) from the start to the end of the scan length. Average of interval measurements was also calculated as an indicator of interval measurements. Effective diameter ($\sqrt{AP * Lat}$)was calculated as stated by AAPM report 204, conversion factors from look up tables of AAPM report No. 204 for 32 cm phantom size were multiplied by CTDIvol to get the SSDE values for series scans with and without TCM as shown in Fig. 3.

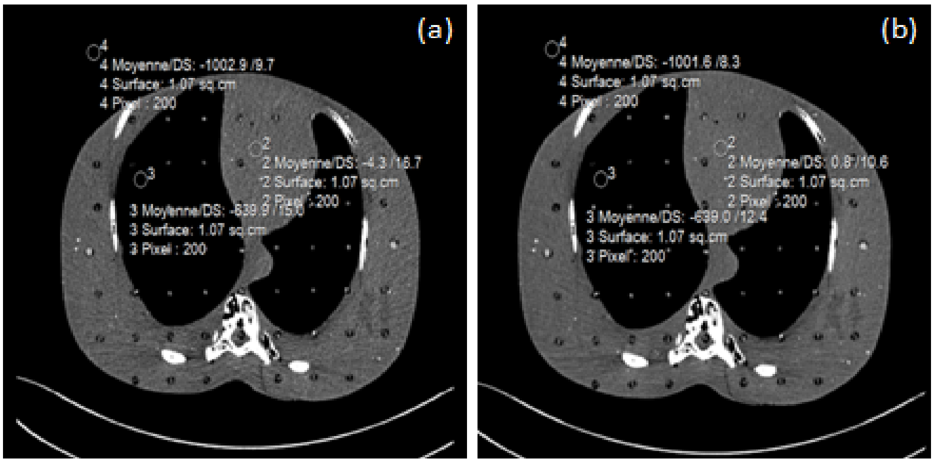

Fig. 4 Phantom ROI's on the same slice position from thoracic protocol without (a) and with CARE Dose 4D (b)

E. Image Evaluation

The image quality was evaluated objectively using SNR. The SNRs were measured in two regions of interest (ROI) with same area placed on a homogeneous object from the phantom as seen in Fig. 4.

The calculation of the SNR was based on the "Rose model" [10]. This model describes the SNR for the detection of a uniform object. The object has an area A in a uniform background with a mean quantum per unit area $\overline{q_b}$ and a mean number of quanta per unit area in the region of the object $\overline{q_0}$ .Thus the SNR is given by (1):

$$\text{SNR}=\frac{A(\overline{q_b}-\overline{q_0})}{\sqrt{A\overline{q_b}}} \quad (1)$$

Rose demonstrated that SNR values equal to five or greater give a reliable detection of an object.

F. CT Data Analysis

The data were analyzed using Statistical Package for the Social Sciences SPSS (version 15.0 for Windows). A paired simple T test was used. A p value of < 0.05 was considered to indicate statistically significant differences.

III. Results

The radiation ED for each protocol was measured to compare the CT scanning protocols with and without TCM. Results were found to be significantly different Table II. For the phantom study, when compared to protocols without TCM, the EDs were reduced significantly with use of TCM for thoracic CT. Without the use of TCM, the ED was 7.01 mSv, and with the use of TCM, the ED was 3.62 mSv. However, when using the CT-expo, ED drops from 6.6 mSv to 3.2 mSv with CARE Dose 4D.

The ED dose values were significantly different ($p<0.05$). The ED was lowered by 48.35% and 51.51% in TCM and CT-expo, respectively.

Similar results for SSDE calculation were found using TCM ($p<0.05$). In addition, SSDE values were of 16.25 mGy and 8.23 mGy without and with TCM, respectively. Thus, SSDE was lowered by 48.8% during CT thoracic phantom scans as shown in Table III.

TABLE II
ED Estimate with and without TCM

Radiation Doses	Without TCM	With TCM
CTDIvol (mGy)	13.41	501.1
DLP (mGy.cm)	6.93	258.9
Phantom ED (mSv)	7.01	3.62
ED reduction (%)	48.35 %	
CT-expo ED (mSv)	6.6	3.2
ED reduction (%)	51.51%	

TABLE III
SSDE WITH AND WITHOUT TCM

Dose radiation	Thoracic without TCM	Thoracic with TCM
CTDIvol (mGy)	13.41	6.93
Effective diameter	29.42	
Conversion factor	1.28	
SSDE (mGy)	16.25	8.32

The objective image noise values performed by the "Rose model" of phantom image scanned with and without CARE Dose 4D are summarized in Table IV. The two ROIs were drowned in two homogenous regions area in the organ and one in the background. SNR values carried out from the same slice were scanned with and without TCM and reconstructed with the same kernel.

TABLE IV
SNR FOR THORACIC SCANS WITH AND WITHOUT CARE DOSE 4D

SNR	Without TCM	With TCM
Protocol Thoracic	11.30	15.40
	31.33	33.66
	11.40	20.60
	31.61	33.66
Statistical Result	P=0.03<0.05	

IV. DISCUSSION

In this study, the ED values were obtained by indirect measurement using the CT-expo calculator and direct measurement using the Rando phantom. The two methods were compared for each scan protocol. Our results showed that, when comparing the two protocols for the same region scanned, the ED is relatively higher if routine protocol without CARE Dose 4D is used. The ED was about 7.01 mSv versus 6.6 mSv without TCM and 3.62 mSv versus 3.2 mSv with TCM for phantom and CT-expo, respectively. Our results revealed a significantly higher percentage of ED reduction in thoracic by using TCM. This result confirmed the result supported by a previous study in which it was shown that TCM can reduce ED by 15% to 53% in adults, depending on the region scanned, without a loss of image quality [11]. Another study [12] has also reported that automated exposure control has the potential to significantly reduce dose in all regions (thoracic, upper abdomen, and pelvis) when used in modern 64-slice CT scanners, without any sacrifice in image quality, and a mean dose reduction of 30.1% of the ED was achieved. Comparing to our result, ED was reduced by a percentage value of 48.35% and 51.51%, respectively, for PDL calculation for ED and CT-expo simulation. Previous study by [13] performed with an adult anthropomorphic phantom found a similar dose reduction by 45.2% in the thorax and abdomen region. Work by [14] showed, for thoracic protocol using phantom study, that the dose reduction achieved with the TCM system in use was determined relative to the dose delivered with the TCM system inactivated. The dose savings ranged from approximately 35% to 60%, depending on the system and the TCM settings.

For thoracic phantom similar, work with and without CARE Dose 4D [15] showed that when they are compared to protocols without TCM, the EDs were reduced significantly with use of TCM for the thoracic CT. With use of TCM, the ED was 6.50±0.29 mSv for thoracic. However, without use of TCM, the ED was 20.07±0.24 mSv, and EDs were reduced by 68%. Our results are also in agreement with those recent studies in phantom.

Comparing between the two methods for ED calculation as illustrated in Table II, the differences between the two methods were statically significant. Results showed that the ED values calculated using the standard methods were different from the ED values calculated with CT-Expo. This result is in agreement with latest study [16]. They showed that, when comparing CT-expo with and without TCM, a statistically significant difference ($p<0.001$) was found for ED on thoracic and abdomen CT, with E being lowered by 4.2% if TCM is considered for examination performed with a 128-multidetector CT with TCM (CareDose 4D, Siemens Definition Flash, Forchheim, Germany). This difference can be explained by the difference in the shape and size of the two phantoms; the difference in slice positions within the two phantoms and the Rando physical phantom size compared with the mathematical phantom.

In the case of SSDE with mAs modulation, dose was reduced by 48.8%, which is in agreement with similar study in phantom using CARE DOSE 4D which showed that dose reduction in SSDE can be achieved when using TCM by 64%–68% for both thoracic and abdomen–pelvic CT [8]. Another study proves the SSDE dose reduction by using TCM, and 68% and 63% of ED reduction can be achieved in thoracic and abdomen–pelvic CT, respectively [15]. Several studies have reported that the patient dose can be quantified by using SSDE, which is a great step forward in monitoring and controlling the CT imaging radiation dose [17], [18].

In the case of image quality, the SNR value validates the "Rose model'' criteria over 5 and they were higher in the image scanned with TCM compared to the same region in the image reconstructed where TCM is inactivated [13]. In agreement with our findings, they reported a significant noise increase and a significant SNR decrease.

In the present work, we approved that CARE Dose 4D as a recent TCM technique which is well established in reducing doses. This approach reduces the dose while maintaining image quality, and then, statistical results related to SNR measurement indicated that CARE Dose using "the Rose model'' criterions still produces an image of sufficient quality for confident diagnosis [19], while dose was well reduced. However, it is difficult to compare the estimated dose reduction values obtained in this study with the values reported in the literature. The results are strongly dependent on the selected scanning parameters, the CT scanner/model, and the specified image quality for the TCM system.

The present study has some limitations. The ideal comparison for this type of study is to have standard and low dose examinations performed on the same patient radiologists and technologists still need to decide which parameters are pertinent to their clinic before accepting the changes described in these protocols. However, ethical principles make this impossible in real practical situation. Therefore, this study suggests a potential for dose modulation and encourages future prospective studies in individual organ dose estimation methods using these techniques during CT scans.

V. Conclusion

Two important findings flow from this study. First, with use of TCM in thoracic CT scans, the radiation doses in terms of ED and SSDE can be reduced significantly by up to 48% to 60%. Secondly, CARE Dose 4D beside ED reduction can give an excellent image quality diagnostic. So, the TCM technique should be used to help in reducing the absorbed dose received by the radiosensitive organs. Thus, this technique is highly recommended to further reduce the radiation dose for thoracic CT examination.

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