ORIGINAL ARTICLE

Radiation dose reduction using two orthogonal topograms associated with automatic tube voltage selection for lung CT scanning as compared with a single anteroposterior topogram

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Abstract

Objective To evaluate the effectiveness of two orthogonal topograms on radiation dose and image quality (IQ) associated with topogram-based automatic tube voltage selection (ATVS) for lung CT scanning.

Methods Thirty-seven patients were enrolled in this study. At baseline, only an anteroposterior topogram was obtained and at follow-up, both anteroposterior and lateral topograms were performed. ATVS was turned on during all scans. Objective and subjective IQ evaluations were performed and compared; tube voltage and radiation dose of each scan were noted and analyzed.

Results A significant difference was observed regarding the objective parameters between baseline and follow-up only in image noise and signal–noise ratio (SNR) in the upper one-third of the image (image noise: 7.49 ± 1.08 vs. 9.10 ± 1.13, $p < 0.001$; SNR: 4.08 ± 0.87 vs. 3.37 ± 0.63, $p < 0.001$). No differences were found between baseline and follow-up in the subjective assessment of IQ. The radiation dose was significantly lower at follow-up than that at baseline (2.73 ± 0.83 mSv vs. 3.55 ± 1.24 mSv, respectively; $p < 0.001$).

Conclusions Using two orthogonal topograms associated with ATVS could significantly reduce the total radiation dose for lung CT scanning, while subjective IQ was maintained.

Keywords Radiation dose · Topogram · Automatic tube voltage selection · ATVS · Lung CT scanning

Introduction

Determining optimal scan settings for individual patients is time-consuming and challenging given the interrelationship among kV, mAs, dose, contrast, and noise. Modern CT devices are equipped with several features to reduce patients' radiation exposure, while maintaining a more constant image quality (IQ). One of the most commonly utilized techniques is automated tube current modulation or so-called automatic exposure control (AEC), which has proven to be effective for balancing radiation exposure and uniform IQ [1–4]. This technique uses localizer radiographs to determine patient size and regional attenuation to adapt tube current based on a specified IQ. In recent years, topogram-based automated tube voltage selection (ATVS) has been used to assist technologists and radiologists in determining the optimal tube voltage for every patient and type of CT examination [5, 6]. This technique uses information generated from the topogram and provided by the user in the slider bar to recommend automatically the optimal kV and mAs; so a user-chosen contrast–noise ratio is maintained, and thus, the optimal IQ and lowest dose are achieved.

In both AEC and ATVS techniques, topograms play an important role. Prior publications suggested the use of a single radiograph for CT planning to reduce the radiation dose

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[7, 8]. Furthermore, Singh et al. [9] concluded that the number and projection of localizer radiographs have a substantial effect on the radiation dose associated with AEC. Acquisition of two orthogonal localizer radiographs is associated with the lowest volumetric CT dose index (CTDIvol) with AEC, as compared with single or double non-orthogonal localizer radiographs. However, little study investigated the effect of the topogram on radiation dose associated with ATVS. So, the purpose of this study was to evaluate the effectiveness of two orthogonal topograms on radiation dose and IQ associated with topogram-based ATVS for a set of lung scans obtained during patient follow-ups.

Methods

Study subjects

This study was approved by the Ethic Committee of our institution, and all patients provided written informed consent. From June 2016 to January 2017, 39 consecutive patients who underwent a non-contrast-enhanced chest CT examination at baseline and follow-up in our hospital were evaluated and 37 patients were enrolled in this study. Patient whose weight, height, BMI or geometric characteristics changed more than 5% between baseline and follow-up will be excluded in the study.

CT data acquisition and reconstruction

All CT scans were performed on a dual-source CT system (Somatom Definition; Siemens Healthcare Forchheim, Germany). During the baseline examination, only an anteroposterior (AP) topogram was performed, but during follow-up, both AP and lateral topograms were performed; the scanning protocol was identical for both baseline and follow-up examinations.

Topogram was scanned in a single breath hold at 100 kV and 35 mAs for both AP and lateral direction, respectively. The radiation dose for each topogram is 0.042 mSv (CTDIvol is 0.08 mGy; dose length product, DLP is 3 mGy cm) and the acquired time is about 10 s (including the breath hold instruction). Topogram-based ATVS (CARE kV, Siemens Healthcare, Forchheim, Germany) and automatic current modulation (CAREDose 4D, Siemens Healthcare, Forchheim, Germany) were switched on. For CARE kV, the "Dose Saving Optimized for" slider was moved to level 3. "Dose Saving Optimized for" slider was designed to determine the exam type according to the diagnostic task. The slider provides 12 levels: level 3 is suggested for non-contrast CT scans, which is designed to achieve optimized dose saving for non-contrast CT scans. Level 11 is suggested for angiography examinations, which is designed to achieve

optimized dose saving for angiography CT scans. For contrast-enhanced scans of parenchymatous organs such as the liver, a setting in between is recommended. For CAREDose 4D, the mAs modulation curve was set to average mode. The IQ reference voltage and current were set at 120 kV and 100 mAs, respectively. Other acquisition parameters were as follows: detector collimation width, $2 \times 32 \times 0.6$ mm; gantry rotation time, 500 ms; and pitch, 1.2.

The raw datasets were reconstructed with an edge-enhancing kernel (B60f) for the lung evaluation and a medium-smooth convolution kernel (B30f) for the soft tissue and mediastinal evaluation in a transverse orientation with 2-mm-thick slices and a 1.5-mm increment. Filtered back projection algorithm was applied for the image reconstruction.

CT image analysis

All datasets were divided into three parts; this is because human body is not a homogeneous cylinder, and the impact of exposure dose reduction on IQ may be various in different parts of body: (1) from the beginning of the scan to the level of the aortic arch, representing the upper one-third of the thorax; (2) from the level of the aortic arch to the level of cardiac base, representing the middle one-third; and (3) from the level of cardiac base to the end of the scan, representing the lower one-third of the thorax.

Objective evaluation of IQ

All objective measurements were performed on a mediastinal window image by a radiologist (M.Z) who was blinded to all clinical information, as well as the scanning protocol. Background noise was defined as the standard deviation of attenuation measured in the air outside the thorax at the level of the sternoclavicular joint (upper one-third), main pulmonary artery (middle one-third), and main portal vein (lower one-third). Attenuation was measured (in HU) in a circular region of interest (ROI) with an area about 2 cm^2 in target vessels at three levels: brachiocephalic artery at the level of sternoclavicular joint, main pulmonary artery at the level of main pulmonary artery and abdominal aorta at the level of main portal vein. ROI was chosen without including parts of the vessel wall, calcification or plaques. SNR was calculated as the quotient of the mean CT attenuation of the vessel and corresponding image noise.

Subjective evaluation of IQ

In the subjective IQ assessments, all the images were labeled with random numbers and only the number of image was provided to the observers to minimize potential bias. Two senior observers (X.F and Y. Z, with 5- and 10-year diagnostic

experience, respectively) who were blinded to the clinical information performed the IQ evaluation independently. A 4-point grading scale was used in the subjective evaluation of IQ on the mediastinal window image and lung window image: score 4 (excellent IQ, clear mediastinal structures, lung markings, and lesions; no artifacts or structural obscurity); score 3 (good IQ, mild artifacts, or structural obscurity); score 2 (moderate IQ, moderate artifacts, or structural obscurity); and score 1 (not evaluable, severe artifacts, or uncharacterizable structures). Images with scores from 2 to 4 were considered of diagnostic IQ; however, a score of 1 was deemed non-diagnostic [10, 11]. The overall IQ score was defined as the lowest score derived from any part (upper, middle and lower) for each patient using different observation windows.

Estimation of radiation dose

The tube voltage, tube current, CTDIvol and dose length product (DLP) were recorded for each examination. Effective radiation dose (ED) was estimated by multiplying the DLP by a conversion factor of 0.014 mSv/(mGy cm), as shown in the formula below [12]:

$$ED = DLP \times k \left(k = 0.014 \text{ mSv}/[\text{mGy cm}] \right).$$

Additionally, the size-specific dose estimate (SSDE) was calculated based on each patient's effective diameter as measured from the axial images at the level of the nipple [13, 14].

Statistical analysis

Statistical analysis was performed using SPSS, version 13.0 (SPSS Inc., Chicago, IL, USA). All quantitative variables are expressed in the form of mean CT values ± standard deviations, and categorical variables are expressed as frequencies or percentages. A paired t test was used to evaluate differences in CT values, image noise, SNR, tube current and effective dose between the two examinations. Wilcoxon signed-rank test was applied to compare the IQ score rated by two readers. Inter-observer variability between the two readers regarding the subjective assessment of IQ was evaluated using κ statistics. A κ value of less than 0.20 indicated poor agreement; a κ value of 0.21–0.40 indicated fair agreement; a κ value of 0.41–0.60 indicated moderate agreement; a κ value of 0.61–0.80 indicated good agreement; and a κ value of 0.81–1.00 indicated very good agreement. The relationship among BMI, patients' geometric characteristics, and dose reduction was analyzed using Pearson's correlation

Table 1 Patient characteristics

Variables	Patients
Sex (M/F)	22/15
Age (years)	46.51 ± 12.27 (range 21–82)
Body weight (kg)	73.03 ± 16.44 (range 40–115)
Height (mm)	168.9 ± 27.91 (range 153–182)
Body mass index (kg/m^2)	25.35 ± 4.16 (range 17.09–37.13)
Lateral dimension(cm)	32.77 ± 3.79 (range 25.03–41.04)
AP dimension (cm)	23.74 ± 3.04 (range 18.17–29.87)
Effective diameter (cm)	27.87 ± 3.17 (range 21.37–34.59)

AP, anteroposterior

Table 2 Objective measurements of image quality on three levels

Anatomic region	Baseline	Follow-up	p value
Mean attenuation (HU)			
Upper one-third	47.54 ± 6.71	48.68 ± 6.95	$p = 0.423$
Middle one-third	44.98 ± 4.45	45.01 ± 4.90	$p = 0.966$
Lower one-third	38.05 ± 6.13	39.24 ± 9.39	$p = 0.349$
Image noise			
Upper one-third	7.49 ± 1.08	9.10 ± 1.13	$p < 0.001$
Middle one-third	8.87 ± 1.12	8.93 ± 1.28	$p = 0.815$
Lower one-third	9.59 ± 1.81	10.10 ± 1.41	$p = 0.069$
SNR of vessel			
Upper one-third	4.08 ± 0.87	3.37 ± 0.63	$p < 0.001$
Middle one-third	3.01 ± 0.47	2.91 ± 0.45	$p = 0.214$
Lower one-third	2.16 ± 0.39	2.02 ± 0.49	$p = 0.056$

Table 3 Subjective image quality assessment on three levels

|	Baseline	Follow-up	p value
Reader 1			
Mediastinal window			
Overall	2.94 ± 0.54	2.89 ± 0.40	$p = 0.527$
Upper one-third	3.40 ± 0.70	3.26 ± 0.61	$p = 0.132$
Middle one-third	3.29 ± 0.52	3.20 ± 0.53	$p = 0.405$
Lower one-third	3.22 ± 0.49	3.17 ± 0.51	$p = 0.527$
Lung window			
Overall	3.57 ± 0.61	3.46 ± 0.56	$p = 0.155$
Upper one-third	3.74 ± 0.44	3.63 ± 0.49	$p = 0.157$
Middle one-third	3.77 ± 0.42	3.74 ± 0.44	$p = 0.763$
Lower one-third	3.71 ± 0.57	3.69 ± 0.53	$p = 0.705$
Reader 2			
Mediastinal window			
Overall	3.06 ± 0.48	3.00 ± 0.49	$p = 0.564$
Upper one-third	3.46 ± 0.56	3.37 ± 0.60	$p = 0.166$
Middle one-third	3.34 ± 0.59	3.29 ± 0.57	$p = 0.705$
Lower one-third	3.29 ± 0.58	3.23 ± 0.49	$p = 0.480$
Lung window			
Overall	3.43 ± 0.56	3.37 ± 0.60	$p = 0.564$
Upper one-third	3.74 ± 0.44	3.68 ± 0.47	$p = 0.527$
Middle one-third	3.71 ± 0.46	3.63 ± 0.49	$p = 0.405$
Lower one-third	3.71 ± 0.52	3.66 ± 0.59	$p = 0.527$
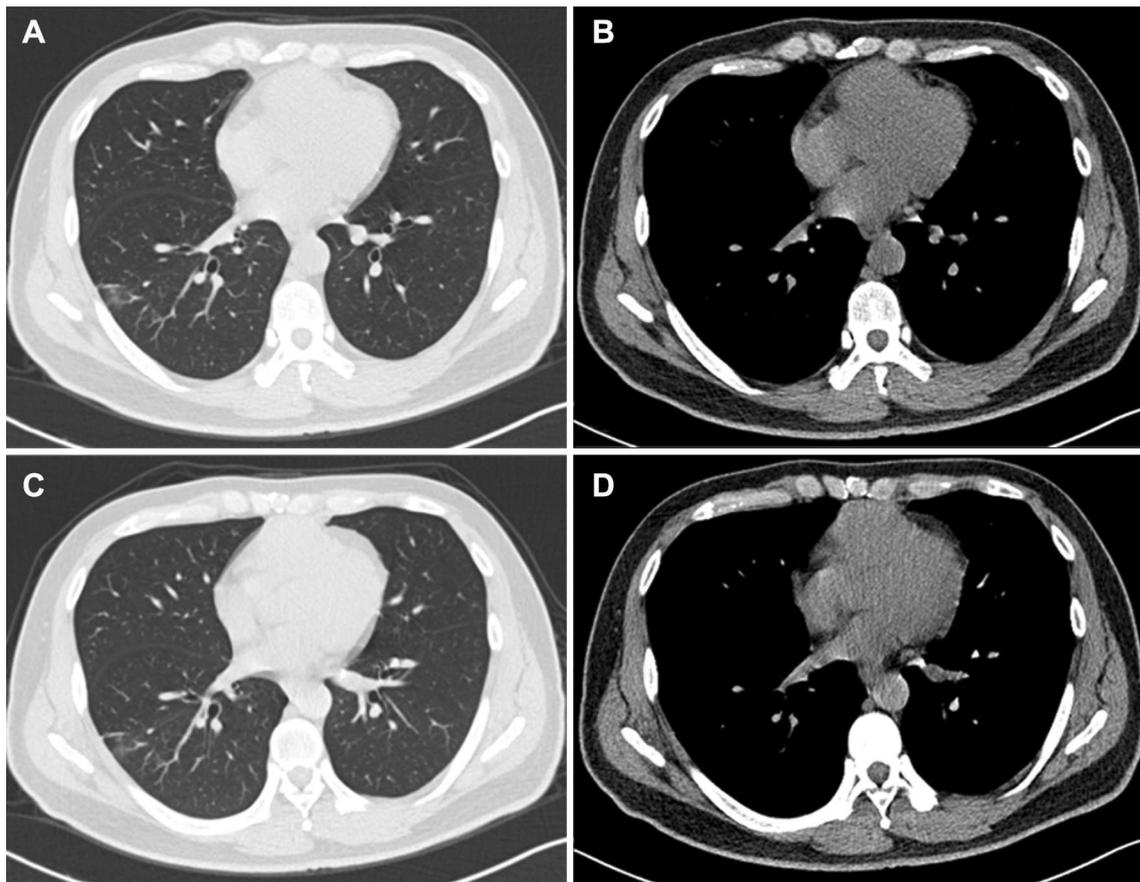
Fig. 1 Lung CT images of a patient with the tube voltage lowered at follow-up. Unenhanced lung CT images show a patchy shadow in the right pulmonary lower lobe of a 47-year-old man (BMI = 27.1 kg/m²). At baseline, according to the attenuation information from a single AP topogram, the scan parameters were set at 140 kVp and 92 mAs automatically, and the radiation dose was 4.99 mSv. At follow-up (5 days later), according to the attenuation information from the two orthogonal topograms, the scan parameters were set at 120 kVp and 105 mAs automatically, and the radiation dose was 3.71 mSv. **a**, **b** Baseline images. **c**, **d** Follow-up images

coefficients. p values less than 0.05 were regarded as significant.

Result

Study population

Two patients were excluded in this study. One was excluded for a weight loss more than 5% at follow-up. Another was excluded for server motion artefacts in follow-up image. For the enrolled 37 patients, the time interval between baseline and follow-up ranged from 3 days to 6 months. Indications for lung CT were known or suspected lung nodules ($n = 25$), interstitial pulmonary disease ($n = 5$), carcinoma ($n = 3$), pneumonia ($n = 2$), and tuberculosis ($n = 2$). The demographic characteristics of the study population, including sex, age, body weight, height, body mass index, and lateral and AP dimensions, are shown in Table 1.

Objective analysis of IQ

Table 2 shows the objective IQ measurements. The mean attenuation showed no statistical difference between baseline and follow-up in any of the 3 levels (all $p > 0.05$). In the upper one-third, image noise at follow-up was higher than that of baseline (9.10 ± 1.13 vs. 7.49 ± 1.08, respectively; $p < 0.001$), but in the middle one-third and lower one-third, image noise showed no significant difference between baseline and follow-up (all $p > 0.05$). The SNR of the vessel in the upper one-third at follow-up was significantly lower than that of baseline (3.37 ± 0.63 vs. 4.08 ± 0.87, respectively; $p < 0.001$), and the SNR of the vessel in the middle one-third and lower one-third exhibited no difference between baseline and follow-up (all $p > 0.05$).
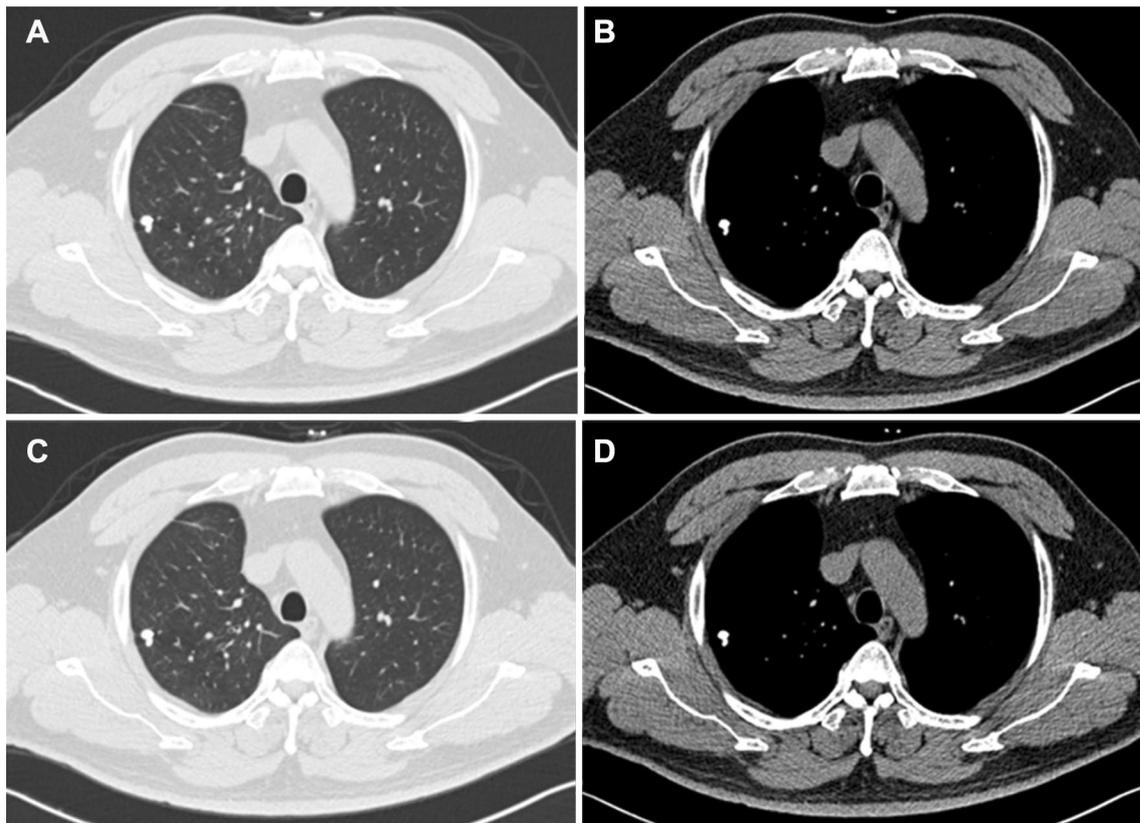
Fig. 2 Lung CT images of a patient without tube voltage changed at follow-up. Unenhanced lung CT images show a calcified nodule in the right pulmonary upper lobe of a 45-year-old man (BMI = 31.2 kg/m^2). At baseline, according to the attenuation information from a single AP topogram, the scan parameters were set at 120 kVp and 133 mAs automatically, and the radiation dose was 4.86 mSv. At follow-up (3 months later), according to the attenuation information from the two orthogonal topograms, the scan parameters were set at 120 kVp and 103 mAs automatically, and the radiation dose was reduced to 3.76 mSv. **a**, **b** Baseline images. **c**, **d** Follow-up images

Table 4 Comparison of radiation dose between baseline and follow-up

	Baseline	Follow-up	Reduction (%)	*p* value
CTDI (mGy)	7.31 ± 2.37	5.61 ± 1.56	20.5 ± 7.3	*p* < 0.001
DLP (mGy cm)	253.78 ± 88.26	195.08 ± 59.06	21.8 ± 7.3	*p* < 0.001
ED (mSv)	3.55 ± 1.24	2.73 ± 0.83	21.8 ± 7.3	*p* < 0.001
SSDE (mGy)	9.43 ± 2.03	7.27 ± 1.25	21.9 ± 7.1	*p* < 0.001

Subjective analysis of IQ

Inter-observer agreement for overall IQ was moderate in mediastinal window assessment ($\kappa = 0.586$), good in lung window assessment ($\kappa = 0.745$) at baseline, and good in both a mediastinal window assessment ($\kappa = 0.616$) and lung window assessment ($\kappa = 0.724$) at follow-up.

For both readers, the IQ scores for all 3 levels at baseline were higher than that of follow-up, but the difference did not reach significance. The IQ scores for both readers are shown in Table 3.

Two representative examples are shown in Figs. 1 and 2. The two cases showed that with the use of two orthogonal topograms, the radiation dose was substantially reduced at follow-up, as compared with baseline, without compromising subjective IQ.

Radiation dose

At baseline, 12 (32.4%) patients were scanned at 100 kV, 20 (54.1%) were scanned at 120 kV, and 5 (13.5%) patients were scanned at 140 kV; at follow-up, 20 (54.1%) were scanned at 100 kV, 17 (45.9%) patients were scanned at 120 kV, and no patient was scanned at 140 kV. As compared with baseline, 13 (35.1%) patients were scanned at a lower tube voltage at follow-up: for 8 patients, the tube voltage

Table 5 Overall subjective image quality assessment for patients with a changed tube voltage

	Baseline	Follow up	*p* value
Reader 1			
Mediastinal window			
Overall IQ	3.08 ± 0.51	2.83 ± 0.390	$p = 0.083$
Lung window			
Overall IQ	3.67 ± 0.49	3.58 ± 0.51	$p = 0.317$
Reader 2			
Mediastinal window			
Overall IQ	3.16 ± 0.58	3.00 ± 0.43	$p = 0.157$
Lung window			
Overall IQ	3.50 ± 0.52	3.41 ± 0.51	$p = 0.564$

IQ, image quality

was reduced from 120 kV to 100 kV; for 5 patients, the tube voltage was reduced from 140 kV to 120 kV. In patients with tube voltage change, $17.40 \pm 13.36\%$ of the tube current was increased at follow-up compared with that at baseline (94.46 ± 12.93 mAs vs. 109.92 ± 11.07 mAs, $p < 0.001$); while in patients without tube voltage change, 18.60 ± 5.77 percent of the tube current was decreased (117.08 ± 17.52 mAs vs. 94.71 ± 11.57 mAs, $p < 0.001$).

At follow-up, the average CTDI, DLP, ED, and SSDE were significantly reduced, as compared with baseline ($20.5 \pm 7.3\%$, $21.8 \pm 7.3\%$, $21.8 \pm 7.3\%$, and $21.9 \pm 7.1\%$, respectively; all $p < 0.001$) (Table 4). For 13 patients for whom the tube voltage was changed, the CTDI and SSDE were reduced: 2.32 ± 1.07 ($26.8 \pm 5.2\%$) and 3.02 ± 1.01 ($28.1 \pm 5.1\%$), respectively; for 24 patients for whom the tube voltage was not changed, the CTDI and SSDE were reduced: 1.23 ± 0.69 ($17.1 \pm 0.59\%$) and 1.69 ± 0.76 ($18.6 \pm 5.8\%$), respectively. Significant differences were found while comparing the dose reduction in patients who did or did not have the tube voltage changed (all $p < 0.001$). Overall subjective IQ for patients with a changed voltage showed no significant difference between baseline and follow-up (Table 5).

The dose reduction increased with BMI or with an increase in the patients' geometric characteristics, which had a strong correlation with BMI ($r = 0.675$, $p < 0.001$), lateral dimension ($r = 0.674$, $p < 0.001$), AP dimension ($r = 0.624$, $p < 0.001$), and effective diameter ($r = 0.697$, $p < 0.001$) (Fig. 3).

Discussion

Topogram-based ATVS has been widely used in clinical practice and could significantly reduce the radiation dose during examination of many body regions while maintaining a good IQ [15–17], but little research has been conducted on the effectiveness of topogram to that of ATVS. The present study showed that the use of two orthogonal topograms associated with ATVS could reduce the radiation dose for patients during a lung scan, as compared with the use of a single AP topogram, without compromising subjective IQ. Topogram acquisition modes can affect the ATVS result, not only the tube current modulation but also the tube voltage selection.

ATVS requires that the automated tube current modulation be turned on and work simultaneously in the following manner: for each patient exam, patient-specific mAs curves are calculated for all kV levels based on the corresponding attenuation information generated by the topogram, and the estimated dose is then calculated based on these kV-specific mAs curves for all kV levels to determine the optimal dose efficiency. Once the optimal settings are determined, the tool checks the system to see if the optimal setting is possible (because of tube current limits, pitch settings, etc.). If this setting is not possible, the next best kV setting is suggested.

For the 13 patients whose scan tube voltage was automatically adjusted to a lower kV at follow-up, the dose reduction was mainly because of the lower voltage scanning. Lowering the tube voltage could significantly reduce the radiation dose because the radiation dose varies in proportion to the square of the tube voltage [18, 19]. According to the ATVS work principle, the optimal kV and mAs setting may not be possible because of an overestimated patient size or inaccurate attenuation information when using a single topogram; thus, the next best kV setting is performed. While two orthogonal topograms could provide more accurate information, the best kV setting may be possible. As the image noise is usually increased when the tube potential is lowered, the ATVS simultaneously adjusts the tube current to compensate for a loss in IQ. Contrast-enhanced CT examinations may be also benefited from lowering the tube voltage, where iodine contrast could be exploited substantially to reduce radiation dose, while maximizing contrast enhancement.

For the other 24 patients whose tube voltage was not changed at follow-up, the dose reduction was mainly because of the automatic current modulation. With a lack of attenuation information from a lateral direction, the axial tube current profiles may not be calculated appropriately; the tube current is mainly determined by the highest X-ray attenuation. However, the human body is not a homogeneous cylinder; X-ray attenuation is different at different angles. Thus, lateral attenuation information is necessary. Two orthogonal topograms could provide more information on patient's physical constitution, which would benefit the calculation of the tube profiles and angular dose modulation. This could account for the difference between baseline and follow-up in image noise and SNR in the upper one-third of the image, in which the lateral attenuation is much higher than the anterior–posterior attenuation.
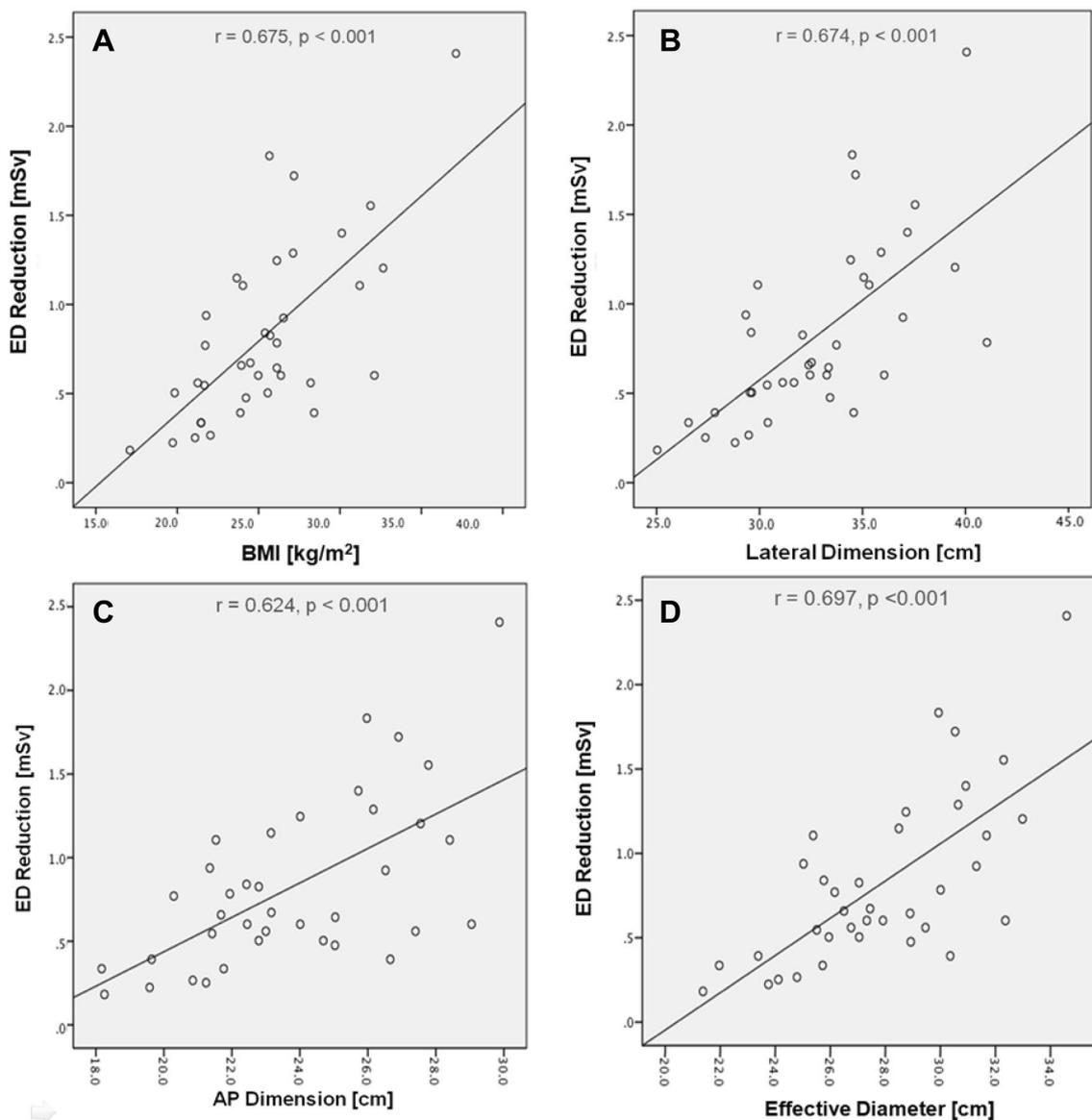
Fig. 3 Pearson's correlation analysis between dose reduction and BMI or patients' geometric characteristics. **a** Dose reduction and BMI, **b** dose reduction and lateral dimension, **c** dose reduction and AP dimension, **d** dose reduction and effective diameter. *BMI* body mass index, *AP* anteroposterior

Some studies found that patients' chest area and BMIs were frequently discordant that could potentially lead to over-radiating patients if using the BMI to select the tube voltage [20, 21]. While Mangold et al. [6] reported that there is a stronger correlation between tube voltage and BMI than between tube voltage and effective diameter; thus, they recommended using the proposed BMI thresholds to define an appropriate tube voltage if ATVS were not available. In the present study, BMI and patients' geometric characteristics including lateral dimension, AP dimension, and effective diameter have a similarly strong correlation with the dose reduction if using two orthogonal topograms with ATVS.

Although one more topogram was performed with an extra radiation dose of 0.042 mSv in the present study, the total radiation dose was significantly reduced for patients during lung CT scanning, which was similar to the result of Singh et al. [9]. Two orthogonal topograms could provide more optimal kV and mAs settings for each individual, which may be more essential for pediatric CT imaging. In addition, although a 10-s extra time is spent to add lateral topogram, the time spent on balancing the interrelationship among kV, mAs, dose, and IQ could be saved substantially for technicians.

There were some limitations in the present study. First, in the present study, the IQ reference voltage and current were set at 120 kV and 100 mAs, respectively, that is used in our routine work. However, the IQ reference parameters may not be the optimal setting or lowest setting from a diagnostic evaluation perspective. The change in IQ reference settings may affect the final result. Second, only one scanner from one CT vendor was applied in the study. The principles of ATVS from different vendors may not be the same; so the results of this study may not apply to CT scanners from other vendors. Third, a relatively small sample set was included in this work. At last, the present study was limited to chest scanning, which has an intrinsically high contrast object with relatively low X-ray density due to the air lung content, while more potentially complex territories with higher density and/or lower intrinsic contrast such as the abdomen or the head were not assessed.

Conclusion

In summary, the present study showed that acquisition of two orthogonal topograms associated with ATVS could significantly reduce the radiation dose in patients with lung CT scanning without a loss in subjective IQ, as compared with a single AP topogram. Topogram acquisition modes can affect the ATVS results, not only the tube current modulation but also the tube voltage selection.

Compliance with ethical standards

Conflict of interest All authors report no conflicts of interest.

Ethical standards This study was approved by the Ethic Committee of the First Hospital of China Medical University, and all patients provided written informed consent.

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