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Evaluation of a Chest Circumference-Adapted Protocol for Low-Dose 128-Slice Coronary CT Angiography with Prospective Electrocardiogram Triggering

Chenying Lu, MD, Zufei Wang, BD, Jiansong Ji, DD, Hailin Wang, BD, Xianghua Hu, BD, Chunmiao Chen, BD

All authors: Department of Radiology, Lishui Central Hospital, The Fifth Affiliated Hospital of Wenzhou Medical College, Lishui, Zhejiang 323000, China

Objective: To assess the effect of chest circumference-adapted scanning protocol on radiation exposure and image quality in patients undergoing prospective electrocardiogram (ECG)-triggered coronary CT angiography (CCTA).

Materials and Methods: One hundred-eighty-five consecutive patients, who had undergone prospective ECG triggering CCTA with a 128-slice CT, were included in the present study. Nipple-level chest circumference, body weight and height were measured before CT examinations. Patients were divided into four groups based on kV/ref·mAs = 100/200, 100/250, 120/200, and 120/250, when patient's chest circumference was ≤ 85.0 (n = 56), 85.0–90.0 (n = 53), 90.0–95.0 (n = 44), and > 95.0 (n = 32), respectively. Image quality per-segment was independently assessed by two experienced observers. Image noise and attenuation were also measured. Signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were calculated. The effective radiation dose was calculated using CT dose volume index and the dose-length product.

Results: A significant correlation was observed between patients' chest circumference and body mass index ($r = 0.762$, $p < 0.001$). Chest circumference ranged from 74 to 105 cm, and the mean effective radiation dose was 1.9–3.8 mSv. Diagnostic image quality was obtained in 98.5% (2440/2478) of all evaluated coronary segments without any significant differences among the four groups ($p = 0.650$). No significant difference in image noise was observed among the four groups ($p = 0.439$), thus supporting the validity of the chest circumference-adapted scanning protocol. However, vessel attenuation, SNR and CNR were significantly higher in the 100 kV groups than in the 120 kV groups ($p < 0.05$).

Conclusion: A measure of chest circumference can be used to adapt tube voltage and current for individualized radiation dose control, with resultant similar image noise and sustained diagnostic image quality.

Index terms: *Chest circumference; Computed tomography; Coronary angiography; Radiation dose; Image quality*

INTRODUCTION

In recent decades, coronary CT angiography (CCTA) has emerged as a fast, accurate, reliable and non-invasive method for the evaluation of coronary artery disease (CAD) (1-3). Previous scanning protocols employed the helical scanning mode with retrospective electrocardiogram (ECG) gating and fixed tube voltage and current with resultant high radiation doses (4, 5). The use of prospective ECG triggering has demonstrated feasibility and substantial reduction in the effective radiation dose to 2.1–5.7 mSv

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Corresponding author: Jiansong Ji, DD, Department of Radiology, Lishui Central Hospital, The Fifth Affiliated Hospital of Wenzhou Medical College, 289 Kuocang Road, Lishui, Zhejiang 323000, China.
• Tel: (8678) 2285501 • Fax: (8678) 2133457
• E-mail: jjstcty@sina.com

(6-8). Furthermore, patient-specific CCTA protocols have recently been proposed for a further dose reduction (9-11).

Body mass index (BMI)-adapted tube voltage and current protocols have been introduced in low-dose scanning protocols (9, 10). The goals were to avoid decreased vessel attenuation and increased image noise in patients with a high BMI, and to avoid unnecessary overexposure in patients with a low BMI. However, BMI as an estimation of body fat does not reliably represent human body shape, especially in female patients or in patients with central obesity, whereas the scan range for CCTA is specifically limited to the chest or the heart.

A recent study by Ghoshhajra et al. (11) has proposed chest measurements as a surrogate for BMI. The study also revealed frequent discordance in patients' chest area and BMI, which may perhaps potentially lead to overdosing in patients when using BMI to select tube potential (kV). However, to the best of our knowledge, no chest circumference-adapted scanning protocol for CCTA with prospective ECG triggering has been evaluated. The purpose of the present study was to evaluate a chest circumference-adapted scanning protocol for low-dose CCTA with prospective ECG triggering.

MATERIALS AND METHODS

Study protocol was approved by our local ethics committee. Potential adverse effects of contrast medium injection and radiation exposure were explained to all the patients by a cardiac radiologist, and written informed consent was obtained before the procedure.

Patient Preparation and CT Examination

One hundred-eighty-five patients (65 women and 120 men) referred for CCTA to rule out CAD were prospectively enrolled between October 2013 and April 2014. Exclusion criteria for the present study were: 1) non-sinus rhythm, 2) heart rate > 75 beats per minute (bpm), 3) allergy to iodinated contrast agent, 4) renal insufficiency (creatinine levels > 1.7 mg/dL), 5) hemodynamic instability, 6) pregnancy, and 7) or Agatston score > 600. None of the subjects had a history of chest surgery, traumatic deformity, or breast augmentation. Under conditions of necessity, oral dose of metoprolol (25–50 mg) was administered 60 minutes before CCTA examination to achieve a heart rate < 75 bpm. Measurement of nipple-level chest circumference using a measuring tape, body weight and height were manually performed by an investigator just before CCTA. A bolus of 80 mL iopamidol (370 mg I/mL) was continuously injected into an antecubital vein at a flow rate of 5 mL/s, followed by 30 mL saline solution. Bolus tracking was performed with a region of interest (ROI) placed into the descending aorta.

All the scans were performed in a prospectively ECG-triggered manner, using a 128-slice Brilliance iCT scanner (Brilliance iCT; Philips Healthcare, Cleveland, OH, USA). Scanning was performed from below the tracheal bifurcation to the diaphragm. Tube voltage and tube current were adapted to individual chest circumference according to the protocol presented in Table 1. The parameters like, slice acquisition, 64 x 0.625 mm; smallest X-ray window (75% of the R-R cycle); z-coverage value of 40 mm with an increment of 35 mm; and gantry rotation time 350 milliseconds were the same for both scan and reconstruction.

Effective Dose Radiation Estimation

Radiation dose parameters were recorded with CT volume dose index (CTDIvol) in mGy; dose-length product (DLP) in mGy·cm and effective dose (ED) in mSv. The CTDIvol and the DLP were automatically determined and recorded from the CT scanner at the end of each examination. For the chest, the ED was calculated by multiplying the DLP by a conversion coefficient (k = 0.014 mSv/mGy·cm) (12).

CCTA Image Evaluation

All the images were evaluated independently by two radiologists with 4 and 5 years of CCTA experience, respectively. Coronary arteries were divided into 16 segments for analysis of CCTA data, as proposed by the American Heart Association (13). Image quality was evaluated on a 4-point scale (1 = excellent, 2 = blurring of the vessel wall, 3 = image with artifacts but evaluative, and 4 = non-evaluative). If there was a discrepancy in the image score between two radiologists, consensus was reached during a joint reading conference.

Quantitative image quality was measured on the basis of image noise, signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR). The ROI were placed at the root of the ascending aorta, the proximal opening of the right coronary artery (RCA), left main artery (LMA) and the adjacent fat tissue peripheral to RCA or LMA. The size of ROI was 70 mm^2 at the aorta root, and as large as possible at RCA, LMA, and perivascular fat. The calcifications, plaques, and stenoses were avoided for ROI placement. The image noise was defined as the standard deviation (SD) of ROI measurement at aorta. The contrast of RCA and LMA was the difference in CT value between the vessel lumen and the adjacent perivascular fat. The SNR was defined as average CT value divided by image noise at the aorta. The CNR in RCA and LMA was defined as the contrast of RCA and LMA divided by image noise.

Statistical Analysis

Statistical analysis was performed using SPSS 19.0 (SPSS Inc., Chicago, IL, USA). Linear regression analysis was performed to compare chest circumference with BMI in all the patients. Continuous variables are expressed as mean ± SD. Categorical variables are expressed as frequencies or proportions. Differences between the four groups were assessed by analysis of variance for the quantitative data and test of equal proportions for the counting data. The interobserver agreement of image quality scoring was tested by Cohen's kappa and was interpreted as moderate for 0.4 < kappa ≤ 0.60, good for 0.6 < kappa ≤ 0.80, and excellent for kappa > 0.80. A p value of < 0.05 was considered statistically significant.

Table 1. Chest Circumference-Adapted Scanning Protocol for CCTA with Prospective ECG Triggering

Chest Circumference (cm)	Voltage (kV)	Current (mAs)
≤ 85	100	200
85–90	100	250
90–95	120	200
> 95	120	250

Note.— CCTA = coronary CT angiography, ECG = electrocardiogram

RESULTS

Patients' Characteristics and Radiation Dose

The characteristics of patients like age, gender distribution and heart rates and specific radiation dose parameters are summarized in Table 2. There was no difference in age (p = 0.734), gender distribution (p = 0.564) and heart rates (p = 0.152) among the four groups. Chest circumference ranged from 74 to 105 cm, and BMI varied from 17.8 to 32.4 kg/m^2. Correlation between chest circumference and BMI is presented in Figure 1. Regression analysis showed a significant correlation between BMI and chest circumference amongst all the patients (r = 0.762, p < 0.001). The effective radiation dose range was from 1.9 to 3.8 mSv.

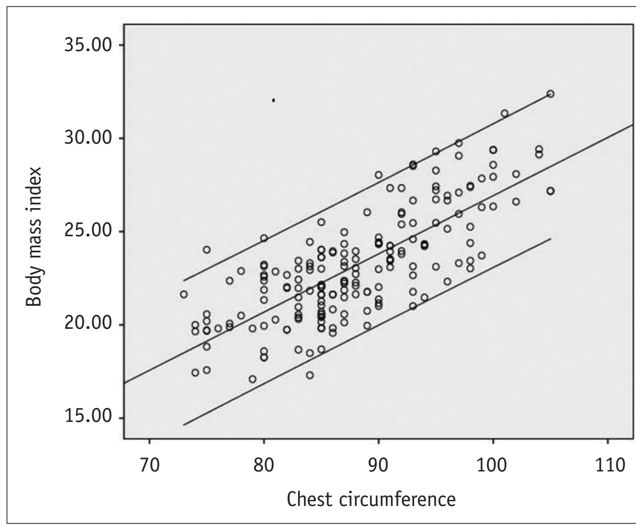

Fig. 1. Linear regression plot showing significant correlation between chest circumference and body mass index (r = 0.762, p < 0.001).

Table 2. Patients' Characteristics and Radiation Dose

	100 kV/200 mAs (n = 56)	100 kV/250 mAs (n = 53)	120 kV/200 mAs (n = 44)	120 kV/240 mAs (n = 32)	P
Female gender	32% (18/56)	38% (20/53)	36% (16/44)	34% (11/32)	0.564
Age (year)	59.9 ± 13.1	62.2 ± 8.0	61.8 ± 12.8	57.4 ± 11.3	0.734
BMI (kg/m^2)	21.8 ± 1.5	23.1 ± 1.6	25.3 ± 2.1	27.7 ± 2.2	< 0.001
CC (cm)	82.7 ± 1.9	87.5 ± 1.6	92.6 ± 1.6	98.5 ± 1.8	< 0.001
HR (bpm)	65.7 ± 5.9	67.1 ± 4.1	67.8 ± 4.9	68.3 ± 5.3	0.152
CTDIvol (mGy)	10.41 ± 0.23	12.91 ± 0.22	17.57 ± 0.18	21.56 ± 0.38	< 0.001
DLP (mGy cm)	135.15 ± 0.18	168.56 ± 0.16	225.39 ± 0.10	272.55 ± 0.28	< 0.001
ED (mSv)	1.90 ± 0.01	2.36 ± 0.01	3.15 ± 0.01	3.82 ± 0.02	< 0.001

Note.— BMI = body mass index, CC = chest circumference, CTDIvol = CT volume dose index, DLP = dose-length product, ED = effective dose, HR = heart rate

Table 3. Qualitative Evaluation of Image Quality

	100 kV/200 mAs	100 kV/250 mAs	120 kV/200 mAs	120 kV/240 mAs	*P*
All	751	716	585	426	
Score 1	604 (80.4%)	601 (83.9%)	502 (85.8%)	354 (83.1%)	0.064
Score 2	109 (14.5%)	93 (13.0%)	68 (11.6%)	55 (12.9%)	0.483
Score 3	23 (3.1%)	12 (1.7%)	8 (1.4%)	11 (2.6%)	0.125
Score 4	15 (2.0%)	10 (1.4%)	7 (1.2%)	6 (1.4%)	0.650
Evaluable	736 (98.0%)	706 (98.6%)	578 (98.8%)	420 (98.6%)	0.650

Note.— Number represents segment. Numbers in parenthesis refer to percentage of segments with score in evaluated segments in group

Table 4. Quantitative Evaluation of Image Quality

	100 kV/200 mAs	100 kV/250 mAs	120 kV/200 mAs	120 kV/240 mAs	*P*
SD, aorta (HU)	35.1 ± 3.4	34.8 ± 2.4	34.4 ± 2.5	35.6 ± 3.8	0.439
Attenuation, aorta (HU)	565.5 ± 108.6	585.3 ± 70.9	450.8 ± 68.3	402.4 ± 54.5	< 0.001
Attenuation, RCA (HU)	604.2 ± 121.5	653.2 ± 80.7	493.3 ± 57.4	445.0 ± 75.1	< 0.001
Attenuation, LMA (HU)	581.3 ± 113.7	632.5 ± 65.5	467.1 ± 55.7	413.0 ± 51.1	< 0.001
SNR, aorta	15.8 ± 3.3	16.8 ± 2.0	14.1 ± 3.4	12.1 ± 2.5	0.018
CNR in RCA	19.4 ± 3.7	21.2 ± 2.7	17.1 ± 3.4	15.2 ± 2.8	0.011
CNR in LMA	18.4 ± 3.7	19.9 ± 2.1	16.5 ± 2.0	14.3 ± 2.4	0.006

Note.— CNR = contrast-to-noise ratio, LMA = left main artery, RCA = right coronary artery, SD = standard deviation, SNR = signal-to-noise ratio

Comparison of Image Quality

Qualitative evaluation of image quality for each group on a per-segment based analysis is shown in Table 3. Evaluation of a total of 2478 coronary artery segments was done in 185 patients. Diagnostic image quality was obtained in 98.5% (2440/2478) of all evaluated coronary segments without any significant differences amongst the four groups ($p = 0.650$). No significant differences were observed among the four groups with regard to individual score rate (all $p > 0.05$). The interobserver agreement was also found to be excellent (kappa = 0.912).

Quantitative image quality parameters are presented in Table 4. There was no difference in image noise among the four groups ($p = 0.439$) (Fig. 2), thus supporting the validity of the chest circumference-adapted scanning protocol. However, the average CT values of the ascending aorta, RCA, and LMA were significantly higher in the 100 kV groups when compared with the 120 kV groups, but there was no significant difference in CT values between the two 100 kV groups and the two 120 kV groups. For SNR in the aorta, CNR in the RCA and LMA, the 100 kV groups were higher when compared with the 120 kV groups ($p < 0.05$).

DISCUSSION

From the time of invention of CT, corresponding advances in diagnostic imaging have been accompanied by considerations about radiation doses. The applied CT dose should be as low as reasonably achievable to reduce the risk of radiation-induced cancer (5, 14, 15). Therefore, reduction in radiations delivered during CCTA to the lowest acceptable dose should be a goal for every CT examination. In the past, several approaches have focused on reducing the effective radiation dose during CCTA examinations (16-19). Large trails have authenticated the use of BMI to adjust radiation dose by modulating tube voltage or current settings in CCTA (9, 10). It has been reported that adaptation of tube current settings to BMI results in constant image noise and reduced radiation dose (10, 16). However, adaptation of tube voltage is also important for reduction in radiation dose, as dose changes with the square of the tube voltage (17, 18). Thus, CCTA with BMI-adapted scanning parameters permits a substantial reduction in radiation dose (9, 10). Nevertheless, BMI may not be an exact estimation of body mass at the level of the heart. For example, characteristics of the upper and lower parts of the thorax differ between men and women, which might be a possible reason for the lack of correlation between BMI and image noise.

A significant correlation between BMI and chest circumference at the nipple level was noted. Therefore, it was speculated that chest circumference might be a better parameter in predicting the appropriate dose parameters, regardless of BMI. For instance, a patient who is very large below the waist may have a large BMI and yet require only

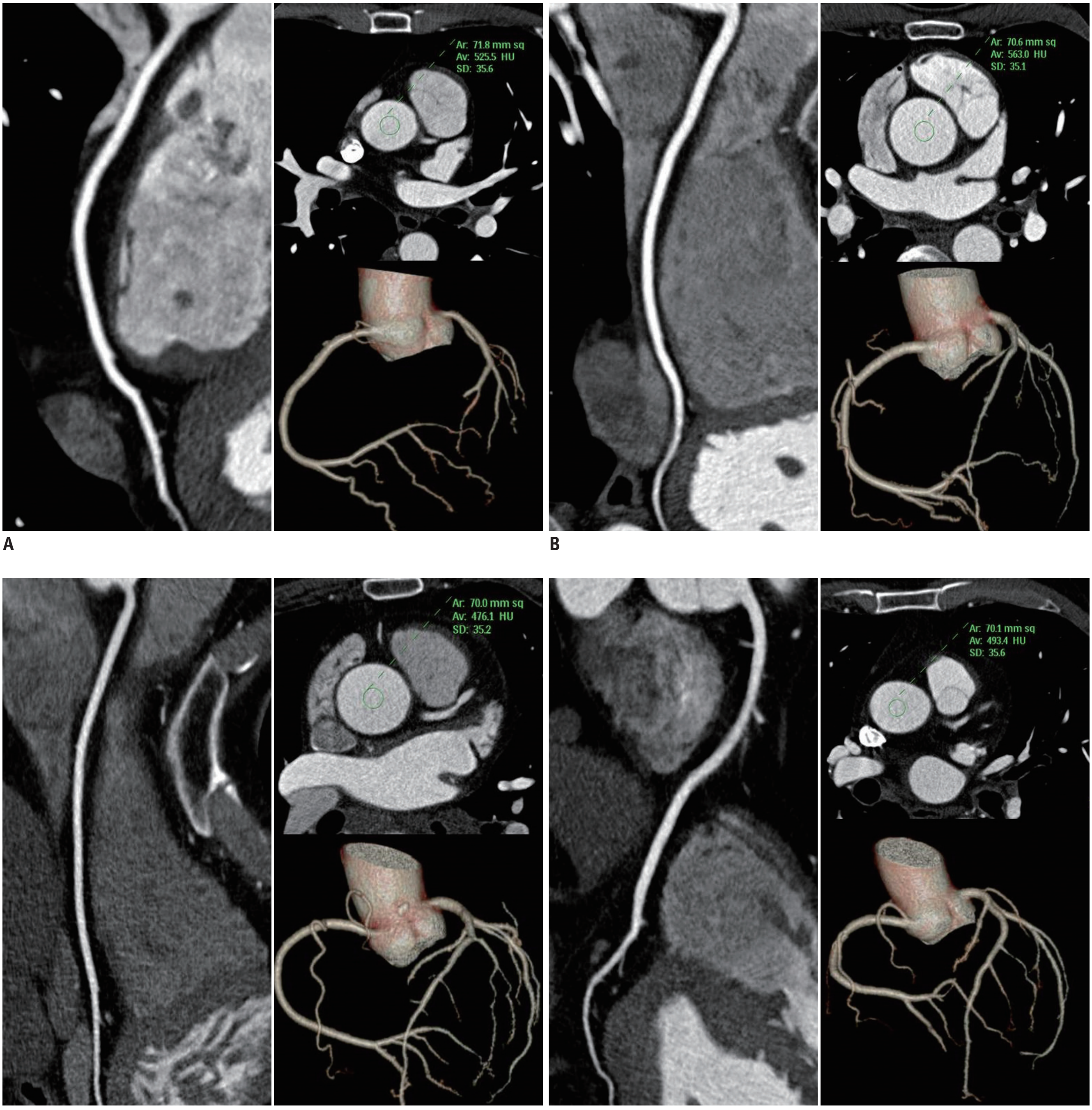

Fig. 2. Curved-planar reconstruction of right coronary artery and volume-rendered trees demonstrating image quality of four CCTA protocols.
A. Tube voltage 100 kV, tube current 200 mAs. **B.** Tube voltage 100 kV, tube current 250 mAs. **C.** Tube voltage 120 kV, tube current 200 mAs. **D.** Tube voltage 120 kV, tube current 250 mAs. ROI was placed at root of ascending aorta and image noise was similar in four groups, while image quality of coronary segments remained diagnostic. CCTA = coronary CT angiography, ROI = region of interest

a relatively small radiation dose for adequate imaging of heart. Conversely, a large-chested woman might require relatively more radiation than a small-chested man with the same BMI (Figs. 3, 4). Menke (20) proposed that body circumferences (thorax, abdomen, pelvis) could possibly be used to optimize radiation doses in CT body imaging.

In our study, chest circumference was employed as an optimizer to assign patients to different scan protocols. Similar image noise was observed in all patients, regardless of chest circumference, and image quality scores indicated no significant differences among the four groups. Therefore, validity of our grouping criterion was confirmed.

Fig. 3. 77-year-old man with BMI of 23.0 and chest circumference of 84.0 cm. Axial CT images obtained at 100 kV and 200 mAs show ascending aorta with image noise of 36 HU and vessel attenuation of 611 HU. BMI = body mass index, HU = Hounsfield unit

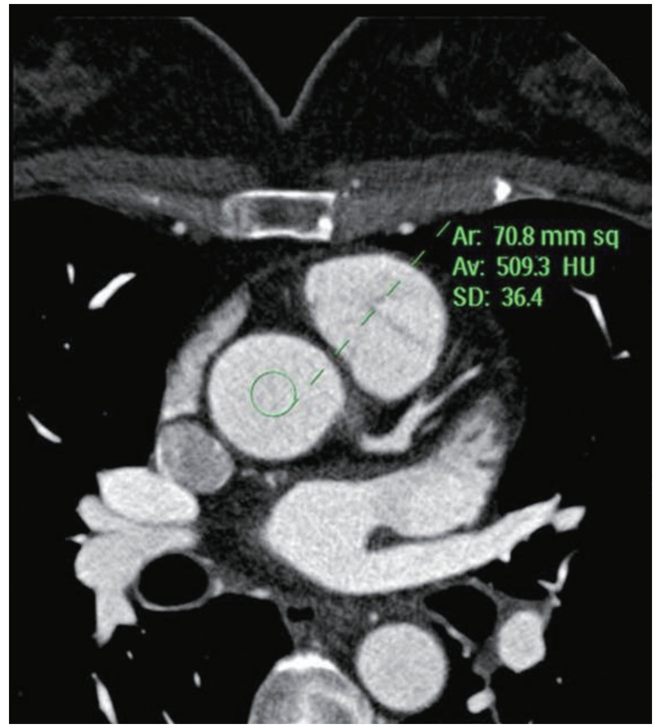

Fig. 4. 45-year-old woman with BMI of 23.1 and chest circumference of 94.0 cm. Axial CT images obtained at 120 kV and 200 mAs show ascending aorta with image noise of 36.4 HU and vessel attenuation of 509.3 HU. This female patient had same BMI, but larger chest circumference, than male patient represented in Figure 3. Image noise was similar when chest circumference-adapted scanning protocol was used. BMI = body mass index, HU = Hounsfield unit

Combining prospective ECG triggering for CCTA with the proposed chest circumference-adapted scanning parameters not only achieved similar image noise for patients of all sizes, but also resulted in a substantial reduction in radiation dose. The effective radiation dose in the present study (1.9–3.8 mSv) was much lower than employed in previous reports (21, 22) of retrospective ECG gating without a chest circumference-adapted scanning protocol (9.4–21.4 mSv). Our study also shows that lowering the tube voltage from 120 kV to 100 kV with subsequent lowering of tube current from 250 mAs to 200 mAs in patients of different chest circumference allows up to 50% reduction in the radiation dose, while maintaining diagnostic quality of the coronary artery segments.

Results of this study demonstrate success of our proposed chest circumference-adapted parameters in compensating chest circumference. However, a decrease in chest circumference was paralleled by an increase in coronary artery attenuation, probably because the contrast bolus was not adapted to chest circumference. On the other hand, a reduction in tube voltage led to an increase in the attenuation of iodinated contrast material with an increase in photoelectric effect and decrease in Compton scattering (23). Consequently, higher mean attenuation of the contrast-filled vascular structures was observed at 100 kV than at 120 kV. The calculation of the SNR and CNR incorporates the attenuation of contrast medium, the attenuation of perivascular fat tissue, and the image noise. Consequently, using 100 kV led to improvement in SNR and CNR due to the fact that the attenuation of the contrast medium increased without increasing the image noise. These results suggest that the amount of contrast material could be decreased, which could reduce the incidence of contrast media-associated nephropathy and could avoid the obscuration of calcification caused by excessively high coronary artery attenuation. It is proposed that the combination of low tube potential, low tube current and reduced contrast material injection protocol should be investigated in future studies.

We acknowledge the following limitations. First, the small number of patients in each group may restrict the value of our results. Second, the dose of contrast medium was not adapted to the scan protocol and chest circumference. However, using only a fixed amount of contrast medium enabled us to evaluate the influence of chest circumference on image noise and coronary vessel attenuation. Third, coronary attenuation and CNR were selectively evaluated in the proximal RCA and LMA. Distal segments were not evaluated because the small diameters of distal segments do not allow placement of an ROI without including parts of the vessel wall and adjacent tissues, thus leading to partial volume effects. Finally, we did not assess the diagnostic accuracy of the four groups for diagnosis of CAD.

In conclusion, it is anticipated that chest circumference could be used to obtain an appropriate tube voltage and current in a personalized approach. The chest circumference-adapted scan protocol in prospectively ECG-triggered CCTA yields images with similar noise regardless of chest circumference. The presented protocol significantly reduces the radiation dose without deteriorating the diagnostic image quality of the coronary arteries.

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