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Image quality and radiation reduction of 320-row area detector CT coronary angiography with optimal tube voltage selection and an automatic exposure control system: comparison with body mass index-adapted protocol

Jiyeon Lim · Eun-Ah Park · Whal Lee ·
Hackjoon Shim · Jin Wook Chung

Abstract To assess the image quality and radiation exposure of 320-row area detector computed tomography (320-ADCT) coronary angiography with optimal tube voltage selection with the guidance of an automatic exposure control system in comparison with a body mass index (BMI)-adapted protocol. Twenty-two patients (study group) underwent 320-ADCT coronary angiography using an automatic exposure control system with the target standard deviation value of 33 as the image quality index and the lowest possible tube voltage. For comparison, a sex- and BMI-matched group (control group, $n = 22$) using a BMI-adapted protocol was established. Images of both groups were reconstructed by an iterative reconstruction algorithm. For objective evaluation of the image quality, image noise, vessel density, signal to noise ratio (SNR), and contrast to noise ratio (CNR) were measured. Two blinded readers then subjectively graded the image quality using a four-point scale (1: nondiagnostic to 4: excellent). Radiation exposure was also measured. Although the study group tended to show higher image noise (14.1 ± 3.6 vs. 9.3 ± 2.2 HU, $P = 0.111$) and higher vessel density (665.5 ± 161 vs. 498 ± 143 HU, $P = 0.430$) than the control group, the differences were not significant. There was no significant difference between the two groups for SNR (52.5 ± 19.2 vs. 60.6 ± 21.8, $P = 0.729$), CNR (57.0 ± 19.8 vs. 67.8 ± 23.3, $P = 0.531$), or subjective image quality scores (3.47 ± 0.55 vs. 3.59 ± 0.56, $P = 0.960$). However, radiation exposure was significantly reduced by 42 % in the study group (1.9 ± 0.8 vs. 3.6 ± 0.4 mSv, $P = 0.003$). Optimal tube voltage selection with the guidance of an automatic exposure control system in 320-ADCT coronary angiography allows substantial radiation reduction without significant impairment of image quality, compared to the results obtained using a BMI-based protocol.

Keywords Low-dose coronary CT angiography · 320-Row area detector CT · Automatic exposure control · Iterative reconstruction · Image quality · Radiation dose

Abbreviations

320-ADCT	320-Row area detector CT
3D	Three-dimensional
AEC	Automatic exposure control
AIDR	Adaptive iterative dose reduction
BMI	Body mass index
Bpm	Beats per minute
CNR	Contrast-to-noise ratio
CT	Computed tomography
CTDI$_{vol}$	Volume CT dose index
D1	First diagonal branch
D2	Second diagonal branch
DLP	Dose-length product
ECG	Electrocardiography
ED	Effective dose
FOV	Field of view
HR	Heart rate
HU	Hounsfield unit
LAD	Left anterior descending artery
LCx	Left circumflex artery
LM	Left main coronary artery
OM	Obtuse marginalis
PDA	Posterior descending artery

J. Lim · E.-A. Park (✉) · W. Lee · J. W. Chung
Department of Radiology, Seoul National University Hospital,
28 Yongon-Dong, Chongno-Gu, Seoul 110-744, Korea
e-mail: iameuna1@gmail.com

H. Shim
Toshiba Medical Systems Korea, Seoul, Korea

| RCA | Right coronary artery |
| SNR | Signal-to-noise ratio |

Introduction

Coronary computed tomography (CT) angiography has been widely used as a primary screening tool for symptomatic patients with suspected coronary artery disease due to its high negative predictive value [1]. Although coronary CT angiography had initially been associated with relatively high radiation exposure levels, various methods such as lower tube voltages, electrocardiography (ECG)-based tube current modulation, and prospective ECG triggering have allowed notable reductions in radiation doses for coronary CT angiography [2]. Automatic exposure control (AEC) systems have also lowered the radiation dose while preserving diagnostic image quality by individually adjusting the tube current according to the patient's attenuation and body habitus [3]. AEC systems for multi-detector CT scanners are now available from all major scanner manufactures under different names, but there have been some limitations in their use for cardiac imaging due to the technical difficulties in conjunction with ECG-based tube current modulation. To date, there have been few studies that have shown that an AEC system using attenuation-based tube current modulation (CareDose 4D; Siemens Medical Solutions, Erlangen, Germany) can reduce radiation exposure, reporting reductions of 22–50 %, for cardiac CT with preserved image quality [4, 5].

Recently, an AEC system (^{SURE}Exposure 3D; Toshiba Medical Systems, Otawara, Japan) that has expanded its function to include cardiac CT has been developed. Among the various ways in which the AEC system operates, ^{SURE}Exposure adopts the standard deviation (noise) as a measure of image quality and aims to match the image noise to the targeted standard deviation [3]. Considering the diagnostic task at hand, ^{SURE}Exposure 3D can provide optimal tube current modulation at each different tube voltage so that a user-chosen image noise value can be maintained. Using lower tube voltages has great advantages, especially in cardiac CT, resulting in higher contrast and preserved signal-to-noise ratios (SNR) when appropriately applied [1]. Until recently, many approaches have used body weight or body mass index (BMI) to manually select the tube voltage and tube current for cardiac CT applications [6–9]. However, these approaches have been documented to be limited, as the attenuation and body habitus in the thorax are often discordant with weight and BMI [10]. Considering that AEC systems are adaptive to the attenuation and body profile of the individual patient,

we hypothesized that coronary CT angiography with optimal tube voltage selection guided by an image noise-targeted AEC system (^{SURE}Exposure 3D) could allow a significant reduction in radiation without a loss of image quality, as compared with that achieved using a BMI-based protocol. Thus, the purpose of our study is to assess the image quality and radiation exposure of 320-ADCT coronary angiography with optimal tube voltage selection and an image noise-targeted AEC system in comparison with those of a BMI-adapted protocol.

Materials and methods

Patients

Our Institutional Review Board approved this retrospective study and waived the requirement for informed consent. From January 2013 to February 2013, 22 consecutive subjects (10 men and 12 women; mean age 61.1 years; range 50–78 years) underwent 320-row area detector CT (320-ADCT) coronary angiography using a built-in AEC system (^{SURE}Exposure; Toshiba Medical Systems, Otawara, Japan), which automatically determined the optimal tube current modulation using a targeted noise standard deviation as the image quality index. This modulation considered many of the scanning and reconstruction parameters as well as the diagnostic task at hand.

To establish a control group, a sex- and BMI-matched group of 22 subjects (10 men and 12 women; mean age 62.9 years; range 44–78 years) who underwent 320-ADCT coronary angiography using a BMI-adapted protocol was selected in reverse chronological order from December to October 2012. Table 1 shows the process of establishing the tube voltage and the tube current with this BMI-adapted protocol. BMI matching between the study and control groups was performed using a stringent BMI difference limit with a mean difference of 0.01 ± 1.88 kg/m^2.

Table 1 Body mass index (BMI)-adapted protocol for the sex- and BMI-matched control group

BMI (kg/m^2)	Voltage (kVp)	Current (mA)
17–18.9	100	450
19–20.9	100	500
21–22.9	100	520
23–24.9	120	400
25–29.9	120	450
30–34.9	120	500
35–39.9	120	580
>40	135	510

All of the subjects included in the study were clinically scheduled for cardiac CT for the evaluation of coronary artery diseases. Patients who had previously undergone coronary artery interventions including stenting and/or coronary artery bypass grafts, those who had heart rates higher than 65 beats per minute (bpm) even after beta-blocker premedication, and patients with arrhythmia were excluded. The body weight, height, and BMI were recorded.

CT scanning protocol

All CT examinations were performed using a 320-ADCT scanner (Aquilion ONE; Toshiba Medical Systems, Otawara, Japan). Patients with a pre-scan heart rate of 65 bpm or higher were given 50–100 mg of oral metoprolol (Betaloc; AstraZeneca, Södertälje, Sweden) 45–60 min prior to the CT examination, unless beta blockers were contraindicated. After scanning for calcium scoring, we administrated 0.4 mg of sublingual nitroglycerin (Nitroquick; Ethex, St. Louis, MO). Then, 60 mL of a nonionic contrast medium (Iomeron 400; Bracco Diagnostics, Milan, Italy) was injected into the antecubital vein at 5 mL/sec, followed by 40 mL of normal saline at the same flow rate, with a dual power injector (Stellant; Medrad, Indianola, PA).

In the study group, 22 patients underwent 320-ADCT coronary angiography using the built-in AEC system ([SURE]Exposure), which automatically determined the optimal tube current based on the target noise (standard deviation [SD]) considered as the index for image quality in this system, which was set at 33 for coronary CT angiography, as recommended by the vendor. The tube voltage was selected as the lowest value possible in so far as the tube current stayed within the limit imposed by the restricted heat capacity. In the control group of 22 patients, the tube voltage and tube current were selected according to the patients' BMI values, as shown in Table 1. All images of both groups were reconstructed using an iterative reconstruction algorithm (adaptive iterative dose reduction 3D, AIDR-3D; Toshiba Medical Systems, Otawara, Japan) with the standard option (Strong: 50 % dose reduction).

The gantry rotation time was 350 ms with the best temporal resolution of 175 ms. As the heart rates of all patients in this study were 67 bpm or less, a single gantry rotation was able to reconstruct all coronary CT angiographic images. Mid-diastolic prospective scanning with an ECG-gated window of 70–80 % of the R–R interval was performed in all subjects.

A field of view (FOV) of a maximal 16 cm in the z-axis, covered by 320 detector rows of 0.5 mm each, permitted the axial volumetric scanning of the range from the mid-ascending aorta to the upper abdomen without table movement. The maximal number of slices was 640 with a 0.5-mm thickness and a 0.25-mm interval using the proprietary double slice technique and cone-beam reconstruction algorithm (coneXact; Toshiba Medical Systems, Otawara, Japan). The number of detectors used for the actual scanning was decided based on the anteroposterior and lateral scanogram images. A medium FOV was selected as it could display all of the relevant cardiac anatomy of every patient within single rotation coverage.

All axial images were reconstructed with a normal soft tissue reconstruction kernel (FC43) with a section thickness of 0.5 mm and a reconstruction interval of 0.5 mm.

CT image analysis

Objective image quality analysis

To analyze the image quality of the coronary arteries objectively, four parameters, the image noise, CT density, SNR, and contrast-to-noise ratio (CNR), were analyzed for each data set by a single reader [11, 12].

Image noise was measured as the standard deviation of CT attenuation measured at the air space outside of the anterior thoracic wall. Subsequently, SNR was calculated by dividing the attenuation of the left main by the image noise. As for CNR, the CT attenuation of the epicardial fat surrounding the artery was measured by placing a region of interest immediately next to the artery and was subtracted from that of the left main coronary artery to find the contrast, which was then divided by the image noise, resulting in the CNR. The four parameters were obtained in the same manner for all images of both groups.

Subjective image quality analysis

For the subjective assessment of image quality, two experienced cardiac radiologists (E.A.P and J.Y.L, having 10 and 3 years of experience, respectively, in cardiac CT) who were blinded to the image groups reviewed the transverse axial CT images in consensus in a randomized order. Decreases in image quality owing to motion and poor gating were not considered in the subjective assessment, as these variables should not be affected by whether the patients belonged in the study group or the control group.

All evaluable coronary artery segments were analyzed using a four-point scale based on the modified American Heart Association 13-segment coronary artery tree [13, 14]; a score of 1 (nondiagnostic) signified impaired image quality with excessive image noise, 2 (adequate) indicated evident limitations in vessel wall definition and in contrast resolution with severe image noise, 3 (good) represented minimal limitations in vessel wall definition and in contrast

resolution with moderate image noise, and 4 (excellent) denoted excellent attenuation in the vessel lumen and clear vessel wall definition with barely perceived image noise (Fig. 1).

The thirteen coronary artery segments were categorized into three segmental classes as follows: (1) proximal segments: proximal right coronary artery (RCA), left main coronary artery (LM), proximal left circumflex artery (LCx), and proximal left anterior descending artery (LAD); (2) mid segments: mid RCA, distal RCA, ramus intermedius, obtuse marginalis (OM), first diagonal branch (D1), and mid LAD; and (3) distal segmental classes: posterior descending artery (PDA), distal LCx, second diagonal branch (D2), and distal LAD. Mean scores were calculated for each segmental class as well as for all three segmental classes as a whole.

Estimation of radiation dose

The volume CT dose index (CTDI$_{vol}$) and the dose-length product (DLP), provided by the scanner system, were documented. The effective dose (mSv) was calculated by multiplying the DLP by a conversion coefficient for the chest (k = 0.014 mSv × mGy^{-1} × cm^{-1}) as the investigated anatomic region [15].

Statistical analysis

All statistical analyses were performed using a statistical software program (SPSS for Windows, version 17.0; SPSS, Chicago, IL, USA). The results of the two groups were compared with each other using Student's t test. For all tests, P values less than 0.05 were considered to indicate statistical significance.

Results

There were no significant differences in the patients' characteristics between the study group and the control group (Table 2). The selected tube voltages used by the AEC-applied and BMI-adapted protocols are listed in Table 3.

Table 4 exhibits the objective and subjective image quality assessment results of the two groups. Although there was a tendency toward higher image noise and vessel attenuation in the study group than in the control group, the differences were statistically insignificant for both image noise ($P = 0.111$) and vessel attenuation ($P = 0.430$), as seen in Figs. 2 and 3. Consequently, there were no significant differences in SNR or CNR between the two groups.

The mean values of the total subjective image quality scores showed no significant differences between the two groups ($P = 0.960$). Furthermore, the mean scores for each segmental class did not significantly differ between the two groups (proximal, 3.57 ± 0.59 vs. 3.64 ± 0.58 for the study group vs. the control group, $P = 0.668$; mid, 3.47 ± 0.55 vs. 3.59 ± 0.57, $P = 0.989$; distal, 3.36 ± 0.56 vs. 3.52 ± 0.59, $P = 0.593$).

Table 4 summarizes the dose parameters of the study and control groups. The mean effective dose was 1.9 ± 0.8 mSv (range 0.2–3.5 mSv) for the study group and 3.6 ± 0.4 mSv (range 2.8–4.1 mSv) for the control group. Radiation exposure was significantly reduced by 42 % in the study group compared with the control group.

Discussion

Our study demonstrated that optimal tube voltage selection guided by an image noise-targeted AEC system (^{SURE}Exposure 3D) with iterative reconstruction for 320-ADCT coronary angiography enabled a marked reduction of the mean effective radiation dose by 42 % without significant impairment to either objective or subjective image qualities, as compared to the BMI-adapted protocol with iterative reconstruction.

An AEC system works by modulating the imparted radiation dose via changes in the tube current–time product

Fig. 1 Representative examples of the different subjective image quality scores for **a** 4 (excellent), **b** 3 (good) and **c** 2 (adequate)

Table 2 Patient characteristics

	Study group (AEC applied)	Control group (BMI adapted)	P value
No. of patients	22	22	
Male gender (%)	45.4	45.4	
Age (years)	61.1 ± 9.7	62.9 ± 8.7	0.985
Body weight (kg)	63.4 ± 7.8	64.3 ± 8.5	0.817
Height (cm)	160.9 ± 8.3	162.3 ± 8.0	0.164
BMI (kg/m^2)	24.3 ± 1.9	24.4 ± 1.9	0.990
Heart rates (bpm)	55.1 ± 6.0	57.1 ± 4.0	0.153

AEC automatic exposure control, *BMI* body mass index

Table 3 Tube potential selection according to body mass index (BMI) in the automatic exposure control (AEC)-applied and BMI-adapted groups

	BMI (kg/m^2)		
	<23	23–25	>25
AEC-applied group (n = 22)			
80 kVp	3	2	0
100 kVp	3	7	7
120 kVp	0	0	0
BMI-adapted group (n = 22)			
80 kVp	0	0	0
100 kVp	6	0	0
120 kVp	0	9	7

(mAs) on the basis of each patient's size and attenuation. AEC systems have a number of potential advantages, including better control of radiation dose, the avoidance of photon starvation artifacts, and a reduced load on the X-ray tube, while being able to maintain image quality in spite of the different attenuation values on CT scans [3]. AEC modulation is performed relatively similarly on most manufacturers' equipment, although the strength of the clinical performance as well as the definition of how the user specifies a minimum acceptable image quality varies across vendors [3, 16, 17]. In cardiac scanning, two AEC systems are usually considered as commercially available due to the technical difficulties in conjunction with ECG-based tube current modulation: CareDose 4D and ^{SURE}Exposure 3D. ^{SURE}Exposure 3D uses a targeted noise standard deviation as the index for image quality, set at 33 for coronary CT angiography, as image noise, when inconsistent, greatly influences diagnostic performance. Image noise depends not only on X-ray intensity but also on the scatter intensity as well as raw data processing parameters. Thus, ^{SURE}Exposure 3D incorporates many factors, such as reconstruction parameters (e.g., slice thickness and filter kernel), scanning parameters (e.g., tube filter, tube voltage, tube current, and exposure time), and patient parameters (e.g., attenuation and body habitus) to sustain a consistent image noise at the user-chosen level in the axial plane and along the z-axis. It is also equipped with

Table 4 Image quality assessment results and dose parameters in the study and control groups

|	Study group (AEC-applied)	Control group (BMI-adapted)	P value
Objective image quality			
Image noise (HU)	14.1 ± 3.6	9.3 ± 2.2	0.111
Left main density (HU)	665.5 ± 161.8	498.2 ± 143.9	0.430
Left main signal to noise	52.5 ± 19.2	60.6 ± 21.8	0.729
Left main contrast to noise	57.0 ± 19.0	67.8 ± 23.3	0.531
Subjective image quality			
Image quality scores			
1	0	0	
2	13	13	
3	111	79	
4	142	158	
Total image score	3.5 ± 0.5	3.6 ± 0.6	0.960
Dose parameters			
CTDI$_{vol}$ (mGy)	9.9 ± 3.0	16.1 ± 1.7	<0.001
DLP (mGy × cm)	132.8 ± 56.8	256.9 ± 28.4	0.003
Effective dose (mSv)	1.9 ± 0.8	3.6 ± 0.4	0.003

Data are presented as means ± standard deviations

AEC automatic exposure control, *BMI* body mass index, *CTDI*$_{vol}$ CT dose index, *DLP* dose length product, *HU* Hounsfield unit
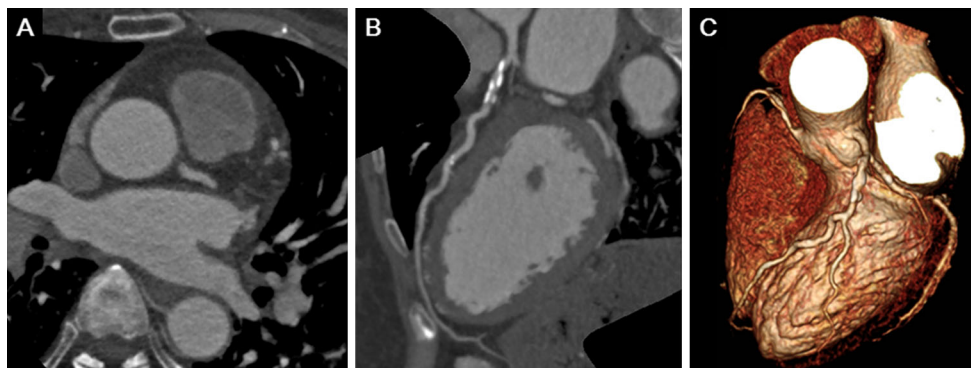
Fig. 2 CT scans obtained in a 57-year-old woman with a BMI of 24.1 (BMI-adapted group) using window width and level of 1,500 HU and 400 HU, respectively. **a** Thin-section transverse axial image, **b** curved multiplanar reformatted image of left anterior descending artery and **c** three-dimensional volume rendered image. Heart rate was 57 beats per minute. Images were scanned in the axial mode (120 kV and 400 mA) and reconstructed with AIDR 3D. The effective radiation dose was 4.0 mSv. The mean image quality score was 4, the image noise was 5.9 HU, and the left main density was 497 HU. The SNR and CNR were 77.4 and 84.2, respectively
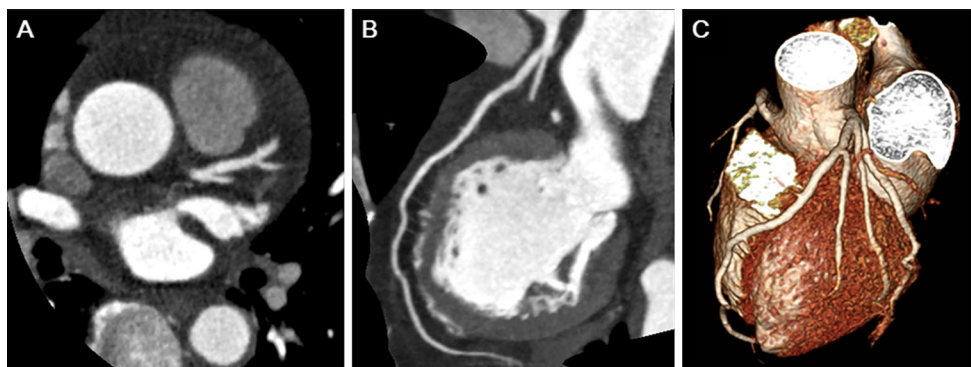
Fig. 3 CT scans obtained in a 60-year-old woman with a BMI of 24.1 (AEC-applied group) using a window width and level of 1,500 and 400 HU, respectively. **a** Thin-section transverse axial image, **b** curved multiplanar reformatted image of left anterior descending artery and **c** three-dimensional volume rendered image. Heart rate was 63 beats per minute. Images were scanned in the axial mode (80 kV and 580 mA) and reconstructed with AIDR 3D. The effective radiation dose was 1.1 mSv. The mean image quality score was 4, the image noise was 10.3 HU, and the left main density was 758 HU. The SNR and CNR were 73.6 and 84.3, respectively

recommended protocol-specific settings so that the tube current can be easily modulated to suit the diagnostic task at hand. In terms of 320-ADCT covering the whole heart in one rotation scan, z-axis tube current modulation is not applied, resulting in a fixed exposure along the z-axis; xy-modulation may play a role in the AEC system. Considering that the body habitus and attenuation distribution along the z-axis would not have much variation through the heart thorax, the z-axis modulation seems not to have much impact on radiation dose reduction. The advantage of an image noise-targeted AEC system (^{SURE}Exposure 3D) over a reference mAs-targeted AEC system (CareDose 4D) is the capacity to allow optimal tube current modulation according to each different tube voltage while maintaining constant image noise.

Extensive studies have proven the feasibility and usefulness of empirical tube voltage lowering [1, 18–20]. Although dose reductions are linear with respect to tube current reduction,

decreases in tube voltage result in an exponential drop in radiation exposure [21]. Another advantage of a lower tube voltage is that it creates higher attenuation levels of iodinated contrast media, compensating for the higher image noise if applied adequately. In addition, until now, most previous studies have used BMI or body weight to select the proper lower tube voltage for each patient. However, Ghoshhajra et al. [22] recently reported a wide discrepancy (39 % discordance) between BMI and chest size, suggesting that BMI may not be the best parameter for tube voltage selection. They also employed an automated attenuation-based tube voltage selection algorithm (CareKV; Siemens Medical Solutions, Erlangen, Germany), which had been recently introduced in body CT as well as cardiac CT. The CareKV program allows the user to select one of twelve settings depending on the diagnostic task at hand and recommends a tube voltage of 70, 80, 100, 120 or 140 kVp, which provides the tube current profile that has the lowest radiation dose as determined by the attenuation and the

body habitus of the patient and the study objective [23]. Ghoshhajra et al. [22] found that this automatic tube voltage selection software improved image quality at a similar radiation dose compared with their standard BMI-based group. In another study, Suh et al. [24] reported that the combination of automatic tube voltage selection with tube current modulation using the iterative reconstruction technique in coronary CT angiography not only improved image quality, but also reduced the radiation dose by up to 30 % on average, while maintaining diagnostic accuracy compared to a BMI-based protocol with filtered back projection. The difference between [SURE]Exposure 3D and CareKV is the target value: [SURE]Exposure 3D performs tube current modulation by keeping the image noise constant according to each different tube voltage and users can select the tube voltage manually. Low tube voltages can be safely used to maintain a constant level of image noise regardless of a patient's BMI value. On the other hand, CareKV offers tube voltage and tube current modulation to maintain the CNR. Another point of distinction from Suh et al.'s study [24] was that we compared iterative reconstructed images in both groups. Even when compared to a BMI-based protocol with iterative reconstruction, we found that the [SURE]Exposure 3D system reduced the radiation dose by up to 40 % on average without any impairment of image quality.

There were some limitations to our study, with the major limitation being that this was a retrospective study performed in a single institution. Although we attempted to minimize confounding factors by matching the sex and BMI values of the two groups, we were not able to perform an intra-individual comparison of signal and dose parameters, as it was not ethically feasible. In addition, the diagnostic accuracy of measurements for the detection of coronary artery disease was not evaluated. Subsequent studies assessing the diagnostic accuracy of this protocol using the AEC system is warranted.

In conclusion, 320-ADCT coronary angiography with optimal tube voltage selection guided by an image noise-targeted tube current modulation system allowed a marked reduction in radiation dose of 42 %, on average, without significant impairment in image quality compared to that attained using a BMI-based protocol.

Conflict of interest Dr Shim is an employee of Toshiba Medical Systems Korea. None of the other authors have disclosed any conflict of interest.

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