

Int J Cardiovasc Imaging (2009) 25:443–451
DOI 10.1007/s10554-008-9397-y

ORIGINAL PAPER

Radiation dose values for various coronary calcium scoring protocols in dual-source CT

Paul Stolzmann · Sebastian Leschka · Thomas Betschart ·
Lotus Desbiolles · Thomas G. Flohr · Borut Marincek ·
Hatem Alkadhi

Received: 26 August 2008 / Accepted: 28 November 2008 / Published online: 12 December 2008
© Springer Science+Business Media, B.V. 2008

Abstract *Purpose* The purpose of this study was to assess the radiation dose and associated image noise of previously suggested calcium scoring protocols using dual-source CT. *Methods* One hundred consecutive patients underwent coronary calcium scoring using dual-source CT. Patients were randomly assigned to five different protocols: retrospective ECG-gating and tube current reduction to 4% outside the pulsing window at 120 (protocol A) and 100 kV (B), prospective ECG-triggering at 120 (C) and 100 kV (D), and prospective ECG-triggering at 100 kV with attenuation-based tube current modulation (E). Radiation dose parameters and image noise were determined and compared. *Results* Protocol A resulted in an effective dose of 1.3 ± 0.2 mSv, protocol B in 0.8 ± 0.2 mSv, protocol C in 1.0 ± 0.2 mSv, protocol D in 0.6 ± 0.1 mSv, and protocol E in 0.7 ± 0.1 mSv. Effective doses were significantly lower ($P < 0.001$) with 100 kV when compared to 120 kV protocols, and were significantly lower ($P < 0.001$) for prospective versus retrospective ECG-gating. No significant difference was found between protocol D and E. Significant negative correlations were found between

the $CTDI_{vol}$ and heart rate for both retrospective ECG-gating protocols (protocol A: $r = -0.98$, $P < 0.001$; protocol B: $r = -0.83$, $P < 0.001$). The mean image noise was 29.0 ± 6.7 HU, with no significant differences between the five protocols. The image noise was significantly correlated with the body weight ($r = 0.21$, $P < 0.05$) and BMI ($r = 0.31$, $P < 0.01$). *Conclusions* Effective dose of calcium scoring using dual-source CT ranges from 0.6 to 1.3 mSv. Prospective triggering and lower tube voltage significantly reduces the radiation but yield similar image noise.

Keywords Coronary calcium scoring · Dual-source computed tomography · Radiation dose

Introduction

Coronary calcium scoring (CS) using computed tomography (CT) has been validated as a tool for optimizing risk stratification regarding the development of non-fatal and fatal cardiac events [1–5]. Recent guidelines from the American Heart Association [6] endorsed the screening using CS as a method to reclassify risk in patients at intermediate risk based on traditional scores such as the Framingham and Procamm algorithms.

CS, being a screening tool, requires the use of low radiation dose techniques in order to outweigh the

P. Stolzmann · S. Leschka · T. Betschart ·
L. Desbiolles · B. Marincek · H. Alkadhi (✉)
University Hospital Zurich, Zurich, Switzerland
e-mail: hatem.alkadhi@usz.ch

T. G. Flohr
Siemens Medical Solutions, Computed Tomography CTE
PA, Forchheim, Germany

potential risks of the examination [6], while at the same time maintain a reasonable image quality, reliability and accuracy [7]. In order to keep radiation exposure as low as reasonably achievable (ALARA), recent modifications of multi-slice CT scanning protocols have been implemented, such as the use of a low tube current [8, 9], attenuation-based tube current modulation [10], and use of low tube voltage protocols [11, 12]. In general, two modes of phase synchronization have been traditionally used, i.e., the retrospective electrocardiography (ECG)-gating technique [13, 14] that acquires continuous data in a helical (spiral) mode and the prospective ECG-triggering technique [15, 16] that obtains data at predefined time points of the cardiac cycle in an axial step-and-shoot mode, the latter usually being associated with a lower radiation dose. Radiation dose can also be significantly reduced in ECG-gated helical (spiral) examinations by using ECG-controlled modulation of the output of the X-ray [17].

The dual-source CT system has been recently introduced which, by virtue of its tube and detector configuration, is characterized by a high and heart rate independent temporal resolution [18]. This allows cardiac scanning of diagnostic image quality even at high and irregular heart rates [19]. In an ECG-gated helical mode, dual-source CT allows the flexible adjustment of the ECG-pulsing window to the individual heart rate [20] and, through adaptation of the spiral pitch to the patient's heart rate, is

characterized by decreasing radiation dose at higher heart rates [21, 22].

The purpose of this study was to assess the radiation dose and associated image noise of previously suggested CS protocols using dual-source CT.

Methods

Study population

One hundred consecutive, asymptomatic patients (38 females, 62 males, mean age 69 ± 11 years, range 44–88 years) were included in this study. All were referred to our department for CS. Personal data including body weight and height were recorded. The body mass index (BMI) was calculated from body weight and height. Patient characteristics are shown in Table 1. Patients with irregular heart rates were not excluded from this study. The study had approval from our local ethical committee who waived the written informed consent requirement.

Dual-source CT calcium scoring protocol

All CS examinations were performed on a dual-source CT scanner (Somatom Definition, Siemens Medical Solutions, Forchheim, Germany) using the following scan parameters: detector collimation $2 \times 32 \times 0.6$ mm, slice acquisition $2 \times 64 \times 0.6$ mm by

Table 1 Patient characteristics ($n = 60$)

	Protocol A	Protocol B	Protocol C	Protocol D	Protocol E	P-Value
Female (%)	6 (30)	6 (30)	10 (59)	5 (25)	11 (55)	0.19
Male (%)	14 (70)	14 (70)	10 (50)	15 (75)	9 (45)	0.19
Age (yrs)	68.6 ± 12.4	69.7 ± 12.4	70.6 ± 11.5	69.9 ± 10.3	65.3 ± 9.9	0.55
BMI (kg/m^2)	26.2 ± 3.3	27.0 ± 4.0	25.2 ± 4.0	25.8 ± 2.2	24.8 ± 3.8	0.23
Heart rate (bpm)	72.2 ± 11.8	69.4 ± 14.2	66.9 ± 15.1	62.5 ± 9.4	68.7 ± 12.1	0.14
Nicotine abuse (%)	7 (35)	5 (25)	9 (45)	6 (30)	9 (45)	0.60
Hypertension (%)	8 (40)	6 (30)	8 (40)	4 (20)	10 (50)	0.34
Hypercholesterolemia (%)	5 (25)	6 (30)	6 (30)	3 (15)	6 (30)	0.78
Diabetes mellitus (%)	3 (15)	2 (10)	4 (20)	2 (10)	2 (10)	0.84
Family history (%)	3 (15)	5 (25)	5 (25)	7 (35)	2 (10)	0.35
Agatston score	380 ± 593	355 ± 513	266 ± 289	215 ± 402	299 ± 527	0.55

Data are presented as rates and frequencies or means \pm SD

Chi-square and Kruskal–Wallis tests were used to assess for significant differences

means of a z-flying focal spot, and gantry rotation time 330 ms. No beta-receptor antagonists for heart rate control were administered prior to CT. The region imaged extended from the level of the aortic root to the diaphragm.

Acquisition techniques and protocols

All 100 patients were randomly assigned to one of the following five CS protocols that were modeled after previously suggested protocols:

Protocol A Retrospective ECG-gating (i.e., helical mode) with ECG-pulsing at 70% of the RR-interval and a reduction of tube current to 4% outside a reconstruction window (minimum width starting at 70% of the RR-interval) using a tube voltage of 120 kV and a tube current time product of 80 mAs per rotation ($n = 20$), in accordance to the literature [10, 23].

Protocol B Retrospective ECG-gating (i.e., helical mode) with ECG-pulsing at 70% of the RR-interval and a reduction of tube current to 4% outside a reconstruction window (minimum width starting at 70% of the RR-interval) using a tube voltage of 100 kV and a tube current time product of 80 mAs per rotation ($n = 20$), in accordance to the literature [12].

Protocol C Prospective ECG-triggering (i.e., axial step-and-shoot mode) with a cycle time of 1.36 s and using a tube voltage of 120 kV and a tube-current time product of 80 mAs per rotation ($n = 20$), in accordance to the literature [15].

Protocol D Prospective ECG-triggering (i.e., sequential mode) with a cycle time of 1.36 s and using a tube voltage of 100 kV and a tube current time product of 80 mAs per rotation ($n = 20$), in accordance to the literature [15].

Protocol E Prospective ECG-triggering (i.e., sequential mode) with a cycle time of 1.36 s and using a tube voltage of 100 kV and an attenuation-based tube current modulation (reference tube current time product set at 80 mAs) ($n = 20$), in accordance to the literature [24].

With the use of an attenuation-based tube current time modulation, the reference tube current time product is modulated in the z-axis direction following the patients' attenuations. When implemented in the cardiac scan template, the tube current is calculated

based on the mean attenuation values derived from the scanogram and set constant for all z-axis positions.

Image reconstruction and data evaluations

All images were reconstructed with a mono-segment reconstruction algorithm [18]. CT data were reconstructed at 70% of the RR-interval using a slice thickness of 3 mm and an increment of 3 mm. All data were transferred to an external workstation; calcifications were quantified with cardiac post-processing software (Syngo CaScore, Siemens) by one experienced observer with 4 years of experience in cardiovascular radiology.

Radiation dose

Dual-source CT behaves similar to conventional CT dose metrics since radiation from both single tubes sum up in a linear manner [21].

The CT volume dose index ($CTDI_{vol}$), being one fundamental radiation dose parameter in CT averages radiation dose over the centre slice of a CT examination consisting of multiple parallel slices [25–27]. Thereby, the numeric value of the $CTDI_{vol}$ is directly related to the degree of overlap between adjacent slices which is determined by the width of the individual slices and by their distance. In the helical scanning mode, the distance between adjacent slices is dependent on how far the patient table advances during one gantry rotation [26]. This so called helical pitch was recorded in all examinations that were done in the helical mode. Scan lengths were noted in all patients. The $CTDI_{vol}$ when using ECG-based tube current modulation is proportional to the average tube current of a single acquisition cycle [21].

The dose-length product (DLP) represents the integrated radiation dose imparted by all slices of a CT examination. The DLP is defined by the scan length, multiplied by the $CTDI_{vol}$ [26].

The parameter of effective dose is an estimate of the dose to patients during an ionizing radiation procedure. It measures the total energy entered into the body and then takes into account the sensitivity of the organs irradiated [25]. The effective dose also allows direct comparison with other sources of radiation exposure, and is the preferred clinical measure of exposure with CT. The effective dose

(Dose_{eff}) was calculated as previously recommended and validated [22, 25, 26, 28].

Image noise

Objective image quality of the five protocols was determined by a radiologist with 4 years of experience in cardiac radiology. To measure image noise, attenuation measures were performed applying a standardized circular region of interest in the ascending aorta at the level of the origin of the coronary arteries on two consecutive axial slices (Fig. 1). The region of interest was defined as large as possible (mean $2.9 \pm 1.4 \text{ cm}^2$, range 1.8–4.3 cm^2) carefully avoiding the vessel wall or plaques. The standard deviations (SD) of the attenuation measurements within the ascending aorta were ascribed to image noise. The mean value of these two measurements was calculated for each patient.

The influence of image noise on CS was assessed. A radiologist (with 2 years of experience in cardiac radiology) who was blinded to the results from objective image quality assessment rated the coronary arteries on a 2-point scale: score 1, image noise adequate for CS; no non-calcified voxels above threshold; score 2, image noise potentially inadequate for scoring; more than one non-calcified voxels above threshold.

Statistical analysis

Categorical variables are expressed as frequencies or percentages. Numerical values of continuous variables are expressed as means and SD.

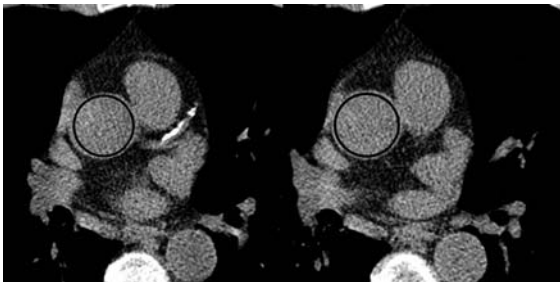


Fig. 1 Image noise measurements. The region of interest was placed into the ascending aorta on two consecutive axial slices and defined as large as possible avoiding partial volume effects. Standard deviations of the attenuation measurements within the ascending aorta were ascribed to image noise. The mean value of both measurements was taken for analysis

Chi-square and Kruskal–Wallis tests were used to assess demographics (i.e., cardiovascular risk factors, heart rate, age, BMI, and Agatston score, as well as scanning range) for significant differences. A *P*-value of less than 0.05 was considered to indicate statistical significance. Pairwise Mann–Whitney–*U* tests of the specific protocols were used to ascertain significance of differences in regard to dose parameters (i.e., CTDI_{vol}, DLP, and Dose_{eff}) and image noise. Image noise was compared for normal (BMI $\leq 25 \text{ kg/m}^2$) and overweight patients (BMI $> 25 \text{ kg/m}^2$) using the Kruskal–Wallis tests. The Kruskal–Wallis test was also used to assess differences between the protocols in the rate of inadequate image noise. According to the Bonferroni method, the level of confidence ($P = 0.05$) was corrected for multiple comparisons between the different protocols. For continuous data (i.e., heart rate, body weight, BMI, CTDI_{vol}, image noise) correlation analysis was performed using Spearman rank order correlation coefficients. Data analysis was performed using commercially available software (SPSS 12.0, Chicago, USA).

Results

All CT examinations were performed without complications. The mean BMI in the 100 patients was $25.2 \pm 3.7 \text{ kg/m}^2$ (range 17.3–35.2 kg/m^2). The mean heart rate during scanning was $67 \pm 13 \text{ bpm}$ (range 43–106 bpm), and the mean scanning range was $128 \pm 20 \text{ mm}$ (range 95–149 mm), with no statistical differences ($P = 0.94$) among the five protocol protocols (Table 2).

Radiation dose

The radiation dose parameters for all protocols are shown in Table 2.

Significant differences ($P < 0.001$) were found between protocol A (i.e., helical 120 kV) and protocol B (i.e., helical 100 kV) for CTDI_{vol}, DLP, and Dose_{eff}. Similarly, significant differences ($P < 0.001$) were revealed for CTDI_{vol}, DLP, and Dose_{eff} values when protocol C (sequential 120 kV) was compared to protocol D (i.e., sequential 100 kV).

We found significant differences ($P < 0.001$) between protocol A (i.e., helical 120 kV) and C (sequential 120 kV) for CTDI_{vol}, DLP, as well as for

Table 2 Radiation dose parameters of different scanning protocols

	Retrospective ECG-gating		Prospective ECG-triggering		
	Protocol A	Protocol B	Protocol C	Protocol D	Protocol E
Scan length	12.9 ± 1.1	12.7 ± 1.5	12.8 ± 1.2	12.9 ± 1.2	12.5 ± 0.7
CTDI _{vol} [mGy]	5.85 ± 0.77	3.71 ± 0.71	4.54 ± 0.01	2.62 ± 0.02	3.10 ± 0.71
DLP [mGy/cm]	75.3 ± 11.7	47.4 ± 12.1	58.3 ± 11.3	33.7 ± 6.5	38.8 ± 7.6
Dose _{eff} [mSv]	1.3 ± 0.2	0.8 ± 0.2	1.0 ± 0.2	0.6 ± 0.1	0.7 ± 0.1

ECG Electrocardiography, CTDI_{vol} CT volume dose index, DLP Dose-length product, Dose_{eff} Effective dose

Data are means ± SD. Scan length was not significantly different between the five different protocols

Dose_{eff}. Protocol B (i.e., helical 100 kV) had significantly ($P < 0.001$) higher CTDI_{vol}, DLP, and Dose_{eff} values when compared to protocol D (i.e., sequential 100 kV).

No significant differences were found when comparing protocol D (i.e., sequential 100 kV) and protocol E (i.e., sequential 100 kV with attenuation-based tube current modulation) regarding CTDI_{vol} ($P = 0.16$), DLP ($P = 0.27$), and Dose_{eff} ($P = 0.27$).

A significant negative correlation was found between CTDI_{vol} and heart rate in protocol A ($r = -0.98$, $P < 0.001$) and B ($r = -0.83$, $P < 0.001$). Scatterplots and correlations are shown in Fig. 2a. No significant correlation was found between CTDI_{vol} and heart rate in protocol C, D, E ($P > 0.05$, Fig. 2b).

CTDI_{vol} values in protocol E (i.e., sequential 100 kV with attenuation-based tube current modulation) showed a significant correlation with the patients body weight ($r = 0.63$, $P < 0.05$) and BMI ($r = 0.84$, $P < 0.01$).

Image noise

In regard to protocols utilizing retrospective ECG-gating, the mean image noise was 28.9 ± 6.4 HU (range 21.0–44.0 HU) in protocol A, and was 32.3 ± 8.1 HU (range 19.0–48.0 HU) in protocol B, respectively (Table 3).

In regard to protocols utilizing prospective ECG-triggering, the mean image noise was 27.2 ± 5.6 HU (range 18.0–39.0 HU) in protocol C, and was 29.3 ± 6.6 HU (range 21.0–44.0 HU) in protocol D, respectively. The mean image noise of protocol E using an attenuation-based tube current modulation was 32.3 ± 5.8 HU (range 22.0–48.0 HU).

In regard to protocols utilizing retrospective ECG-gating, no significant difference ($P = 0.18$) were

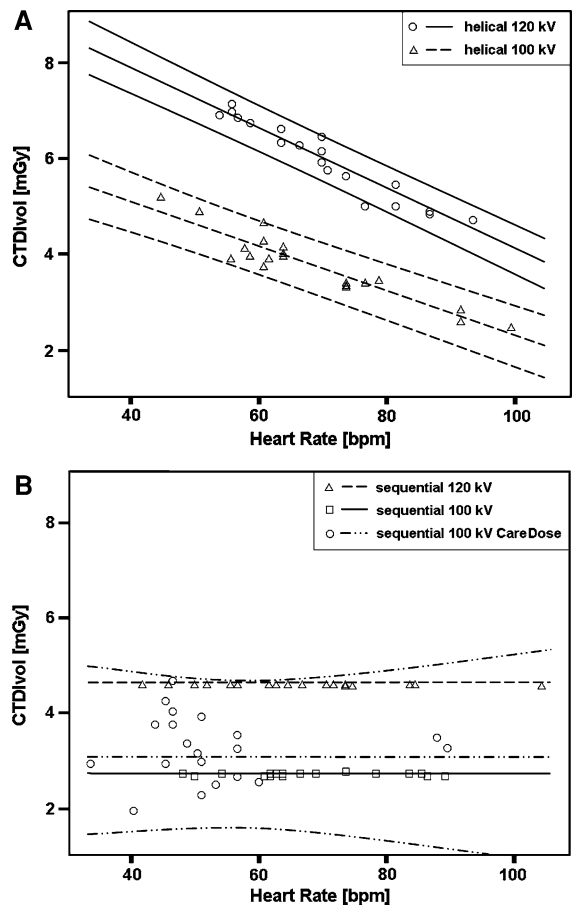


Fig. 2 Scatterplots and correlation between CTDI_{vol} [mGy] and heart rate [bpm] for the different protocols. **a** A significant negative correlation was found for the helical protocol at both tube voltages ($r = -0.98$ and $r = -0.83$, $P < 0.001$, respectively). **b** No significant correlation was found for all sequential protocols ($P = n.s.$)

found between protocol A (i.e., helical 120 kV) and protocol B (i.e., helical 100 kV) for image noise. Similarly in regard to protocols utilizing prospective

Table 3 Image noise of the different calcium scoring protocols

	Image noise	Protocol A	Protocol B	Protocol C	Protocol D	Protocol E
Protocol A	28.9 ± 6.4	–	0.18	0.60	0.93	0.12
Protocol B	32.3 ± 8.1	n.s.	–	0.06	0.23	0.86
Protocol C	27.2 ± 5.6	n.s.	n.s.	–	0.48	0.05
Protocol D	29.3 ± 6.6	n.s.	n.s.	n.s.	–	0.06
Protocol E	32.3 ± 5.8	n.s.	n.s.	n.s.	n.s.	–

Data are presented as means ± standard deviation. The Mann–Whitney-*U* test was used to test for the significance of differences

ECG-triggering, image noise did not differ significantly ($P = 0.48$) when protocol C (sequential 120 kV) was compared to protocol D (i.e., sequential 100 kV).

We did not find significant differences between protocol A (i.e., helical 120 kV) and C (sequential 120 kV) ($P = 0.60$), and between protocol B (i.e., helical 100 kV) and protocol D (i.e., sequential 100 kV) ($P = 0.23$). Because the mean image noise of all protocols was comparable (Fig. 3), the mean image noise was calculated with 29.0 ± 6.7 HU.

No significant differences were found when comparing protocol D (i.e., sequential 100 kV) and protocol E (i.e., sequential 100 kV with attenuation-based tube current modulation) ($P = 0.06$).

No significant differences were found when comparing the image noise in normal weight patients between the protocols ($P = 0.17$). In regard to image noise in overweight patients, significant differences were found ($P < 0.05$), with a higher mean image noise using 100 kV protocols.

The image noise of all patients was significantly correlated with the body weight ($r = 0.21$, $P < 0.05$) and BMI ($r = 0.31$, $P < 0.01$). When correlating the image noise with the body weight and BMI for the protocols separately, no level of significance was found for any protocol except of protocol B (body weight, $r = 0.51$, $P < 0.05$; BMI, $r = 0.50$, $P < 0.05$).

In regard to protocols utilizing retrospective ECG-gating, coronary arteries were rated as having a score 1 in 20/20 patients (100%) using protocol A and in 18/20 patients (90%) with protocol B.

In regard to protocols utilizing prospective ECG-triggering, coronary arteries were rated as having a score 1 in 19/20 segments (95%) using protocol C, in 18/20 segments (90%) with protocol D, and in 17/20 patients (85%) with protocol E, respectively. Non-calcified voxels above the threshold were exclusively present in the posterior descending artery in 5/8 patients (63%). The rate of coronary arteries with inadequate image noise (score 2) was not significantly different ($P > 0.05$) among the five different protocols.

Discussion

This study shows that the effective radiation dose for coronary CS using dual-source CT ranges between 0.6 and 1.3 mSv, depending on the protocol used. Prospective triggering significantly reduced the radiation dose when compared to the retrospectively ECG-gated protocols when using a similar tube voltage. The $CTDI_{vol}$ showed a significant negative correlation with increasing heart rates while using the retrospective ECG-gating protocol. The reduction of



Fig. 3 Image examples of the five protocols in five different male patients having a body mass index between 27.3 and 28.2 kg/m². Coronary arteries were considered to be depicted with adequate image noise for calcium scoring. **a** Helical

120 kV. **b** Helical 100 kV. **c** Sequential 120 kV. **d** Sequential 100 kV. **e** Sequential 100 kV with attenuation-based tube current modulation

the tube potential was associated with a significant reduction in radiation dose for both phase synchronizing techniques. Despite of the various dose characteristics, all protocols yielded similar image noise levels.

Although the usefulness of CS with regard to risk stratification has been proven in a number of studies [1–3], the optimal CT scanning protocols are still a matter of discussion [6, 7, 29–33]. Some authors have demonstrated the best reproducibility for the retrospective ECG-gating technique [13, 15, 30]. This becomes important when tracking changes over time in order to assess the efficacy of therapies [6]. Because protocols using retrospective ECG-gating are generally associated with a higher dose as compared to protocols employing the prospective technique, various efforts have been made for developing and optimizing dose saving algorithms for retrospective ECG-gated CT [12, 17, 18, 34, 35].

The heart rate adapted pitch of dual-source CT has been previously shown to be the major contributor to minimized dose at higher heart rates [21, 22]. The $CTDI_{vol}$ in our study significantly correlated with the heart rate for both retrospectively ECG-gated protocols. In a recent CT coronary angiography study of Stolzmann et al. [22], the authors have found no significant correlation between $CTDI_{vol}$ and heart rate when using the 4% tube current reduction protocol. In contrast, this study shows a significant correlation between $CTDI_{vol}$ and heart rate that can be explained by the fact that for CS, in contrast to CT coronary angiography, the ECG-pulsing window can be kept narrow also at higher heart rates.

It has been shown that lower tube voltages considerably reduce the radiation dose of CT examinations [11, 36, 37]. For CS, this relevant dose reduction is possible without compromising the reproducibility and accuracy of the method. At lower tube voltages, however, the detection threshold needs to be increased because of the increasing attenuation of calcium at lower photon energy levels [37].

With a reduction of tube potential from 120 kV to 100 kV, it is possible to save approximately 37% of the delivered radiation dose when using retrospective ECG-gating and approximately 40% when using the prospective ECG-triggering technique.

Recently, Muhlenbruch et al. [10] showed that use of attenuation-based tube current for CS leads to a more balanced image noise and reduces the radiation

dose as compared to a fixed tube current. By doing so, the dose usage can be optimized without overexposure in low weighted or underexposure in overweight patients. In our study, the use of attenuation-based tube current resulted in a $CTDI_{vol}$ that significantly correlated with the weight and BMI of the patients, as expected. As compared to the fixed tube current protocol, a slight but non-significant increase of the $CTDI_{vol}$ was noted that is most likely explained by our population being on average overweight.

Interestingly in our study, besides significant reductions radiation dose were found, all protocols yielded similar image noise. However, image noise differed among the five protocols when only considering overweight patients. In contrast to Mahnken et al. [38] who described a mean image noise level of 19 HU, we observed a slightly higher mean image noise of 29.0 HU. The main reason for this is that the tube voltage in the study by Mahnken et al. [38] was set to 140 kV whereas in our study all scans were performed at either 100 or 120 kV in this overweight patient cohort leading to an increased image noise. However, the measured mean image noise levels were close to the image noise recommendation for coronary calcium scoring of 25 HU [10].

Study limitations

First, we have not assessed the accuracy and reproducibility of the various coronary CS protocol tested in this study. However, this was not the purpose of this study which rather aimed to determine radiation dose parameters associated with the various protocols. Certainly, future studies must aim at an evaluation of the most accurate and robust dual-source CT CS protocol being associated with the lowest possible radiation dose [7]. Second, we used in most protocols a fixed tube current time product of 80 mAs per rotation as recommended by the vendor. This might not reflect the optimal tube current with regard to accuracy and radiation dose, which let appear our dose calculations being relatively arbitrary. A recent phantom study on CS has shown that size-specific tube current values yielded comparable data among different patient sizes and thus recommended the implementation of adjusted tube current time product settings for small, medium and large patients [9]. This is in line with the results from the

study of Muhlenbruch et al. [10] who adjusted—similar to our protocol E—the tube current to the patients body constitution by means of attenuation-based tube current modulation.

Conclusion

Radiation dose of CS using dual-source CT ranges between 0.6 and 1.3 mSv, depending on the type of data acquisition and the protocol used. Prospective triggering significantly reduces the radiation dose delivered to patients as compared to the retrospective ECG-gating mode. A reduction of tube potential leads to significant reductions in radiation dose irrespective of whether the retrospective or prospective mode is applied. Both strategies may be implemented without an increase in image noise in normal weight patients. Further studies must aim at an assessment of the optimal CS protocol for dual-source CT with regard to the accuracy and reproducibility of coronary calcium burden quantification.

Acknowledgments This research has been supported by the National Center of Competence in Research, Computer Aided and Image Guided Medical Interventions (NCCR CO-ME) of the Swiss National Science Foundation.

References

- Arad Y, Spadaro LA, Goodman K, Newstein D, Guerci AD (2000) Prediction of coronary events with electron beam computed tomography. *J Am Coll Cardiol* 36:1253–1260. doi:[10.1016/S0735-1097\(00\)00872-X](https://doi.org/10.1016/S0735-1097(00)00872-X)
- Raggi P, Callister TQ, Cooil B, He ZX, Lippolis NJ, Russo DJ, Zelinger A, Mahmarian JJ (2000) Identification of patients at increased risk of first unheralded acute myocardial infarction by electron-beam computed tomography. *Circulation* 101:850–855
- Carr JJ, Nelson JC, Wong ND, McNitt-Gray M, Arad Y, Jacobs DR Jr, Sidney S, Bild DE, Williams OD, Detrano RC (2005) Calcified coronary artery plaque measurement with cardiac CT in population-based studies: standardized protocol of multi-ethnic study of atherosclerosis (MESA) and coronary artery risk development in young adults (CARDIA) study. *Radiology* 234:35–43. doi:[10.1148/radiol.2341040439](https://doi.org/10.1148/radiol.2341040439)
- Shareghi S, Ahmadi N, Young E, Gopal A, Liu ST, Budoff MJ (2007) Prognostic significance of zero coronary calcium scores on cardiac computed tomography. *J CCT* 1:155–159
- de Vos AM, Rutten A, van der Zaag-Loonen HJ, Bots ML, Dikkers R, Buiskool RA, Mali WP, Lubbers DD, Mosterd A, Prokop M, Rensing BJ, Cramer MJ, van Es HW, Moll FL, van de Pavoordt ED, Doevendans PA, Velthuis BK, Mackaay AJ, Zijlstra F, Oudkerk M (2008) Non-invasive cardiac assessment in high risk patients (the ground study): rationale, objectives and design of a multi-center randomized controlled clinical trial. *Trials* 9:49. doi:[10.1186/1745-6215-9-49](https://doi.org/10.1186/1745-6215-9-49)
- Budoff MJ, Achenbach S, Blumenthal RS, Carr JJ, Goldin JG, Greenland P, Guerci AD, Lima JA, Rader DJ, Rubin GD, Shaw LJ, Wiegers SE (2006) Assessment of coronary artery disease by cardiac computed tomography: a scientific statement from the American Heart Association Committee on Cardiovascular Imaging and Intervention, Council on Cardiovascular Radiology and Intervention, and Committee on Cardiac Imaging, Council on Clinical Cardiology. *Circulation* 114:1761–1791. doi:[10.1161/CIRCULATIONAHA.106.178458](https://doi.org/10.1161/CIRCULATIONAHA.106.178458)
- Raggi P (2008) Too many options for computed tomography for coronary calcium screening can we strike a balance between accuracy and radiation exposure? *Acad Radiol* 15:955–957. doi:[10.1016/j.acra.2008.06.001](https://doi.org/10.1016/j.acra.2008.06.001)
- Horiguchi J, Yamamoto H, Hirai N, Akiyama Y, Fujioka C, Marukawa K, Fukuda H, Ito K (2006) Variability of repeated coronary artery calcium measurements on low-dose ECG-gated 16-MDCT. *AJR Am J Roentgenol* 187:W1–W6. doi:[10.2214/AJR.05.0052](https://doi.org/10.2214/AJR.05.0052)
- McCullough CH, Ulzheimer S, Halliburton SS, Shanneik K, White RD, Kalender WA (2007) Coronary artery calcium: a multi-institutional, multi-manufacturer international standard for quantification at cardiac CT. *Radiology* 243:527–538. doi:[10.1148/radiol.2432050808](https://doi.org/10.1148/radiol.2432050808)
- Muhlenbruch G, Hohl C, Das M, Wildberger JE, Suess C, Klotz E, Flohr T, Koos R, Thomas C, Gunther RW, Mahnken AH (2007) Evaluation of automated attenuation-based tube current adaptation for coronary calcium scoring in MDCT in a cohort of 262 patients. *Eur Radiol* 17:1850–1857. doi:[10.1007/s00330-006-0543-4](https://doi.org/10.1007/s00330-006-0543-4)
- Abada HT, Larchez C, Daoud B, Sigal-Cinquandre A, Paul JF (2006) MDCT of the coronary arteries: feasibility of low-dose CT with ECG-pulsed tube current modulation to reduce radiation dose. *AJR Am J Roentgenol* 186:S387–S390. doi:[10.2214/AJR.05.0216](https://doi.org/10.2214/AJR.05.0216)
- Jakobs TF, Wintersperger BJ, Herzog P, Flohr T, Suess C, Knez A, Reiser MF, Becker CR (2003) Ultra-low-dose coronary artery calcium screening using multislice CT with retrospective ECG gating. *Eur Radiol* 13:1923–1930. doi:[10.1007/s00330-003-1895-7](https://doi.org/10.1007/s00330-003-1895-7)
- Kopp AF, Ohnesorge B, Becker C, Schroder S, Heuschmid M, Kuttner A, Kuzo R, Claussen CD (2002) Reproducibility and accuracy of coronary calcium measurements with multi-detector row versus electron-beam CT. *Radiology* 225:113–119. doi:[10.1148/radiol.2251010173](https://doi.org/10.1148/radiol.2251010173)
- Ulzheimer S, Kalender WA (2003) Assessment of calcium scoring performance in cardiac computed tomography. *Eur Radiol* 13:484–497
- Horiguchi J, Kiguchi M, Fujioka C, Arie R, Shen Y, Sunasaka K, Kitagawa T, Yamamoto H, Ito K (2008) Variability of repeated coronary artery calcium scoring and radiation dose on 64- and 16-slice computed tomography by prospective electrocardiographically triggered axial and retrospective electrocardiographically gated spiral

- computed tomography: a phantom study. *Acad Radiol* 15:958–965. doi:[10.1016/j.acra.2008.03.007](https://doi.org/10.1016/j.acra.2008.03.007)
16. Scheffel H, Alkadhi H, Leschka S, Plass A, Desbiolles L, Guber I, Krauss T, Gruenenfelder J, Genoni M, Luescher TF, Marincek B, Stolzmann P (2008) Low-dose CT coronary angiography in the step-and-shoot mode: diagnostic performance. *Heart* 94(9):1132–1137
 17. Jakobs TF, Becker CR, Ohnesorge B, Flohr T, Suess C, Schoepf UJ, Reiser MF (2002) Multislice helical CT of the heart with retrospective ECG gating: reduction of radiation exposure by ECG-controlled tube current modulation. *Eur Radiol* 12:1081–1086. doi:[10.1007/s00330-001-1278-x](https://doi.org/10.1007/s00330-001-1278-x)
 18. Flohr TG, McCollough CH, Bruder H, Petersilka M, Gruber K, Suss C, Grasruck M, Stierstorfer K, Krauss B, Raupach R, Primak AN, Kuttner A, Achenbach S, Becker C, Kopp A, Ohnesorge BM (2006) First performance evaluation of a dual-source CT (DSCT) system. *Eur Radiol* 16:256–268. doi:[10.1007/s00330-005-2919-2](https://doi.org/10.1007/s00330-005-2919-2)
 19. Matt D, Scheffel H, Leschka S, Flohr TG, Marincek B, Kaufmann PA, Alkadhi H (2007) Dual-source CT coronary angiography: image quality, mean heart rate, and heart rate variability. *AJR Am J Roentgenol* 189:567–573. doi:[10.2214/AJR.07.2078](https://doi.org/10.2214/AJR.07.2078)
 20. Leschka S, Scheffel H, Desbiolles L, Plass A, Gaemperli O, Valenta I, Husmann L, Flohr TG, Genoni M, Marincek B, Kaufmann PA, Alkadhi H (2007) Image quality and reconstruction intervals of dual-source CT coronary angiography: recommendations for ECG-pulsing windowing. *Invest Radiol* 42:543–549. doi:[10.1097/RLI.0b013e31803b93cf](https://doi.org/10.1097/RLI.0b013e31803b93cf)
 21. McCollough CH, Primak AN, Saba O, Bruder H, Stierstorfer K, Raupach R, Suess C, Schmidt B, Ohnesorge BM, Flohr TG (2007) Dose performance of a 64-channel dual-source CT scanner. *Radiology* 243:775–784. doi:[10.1148/radiol.2433061165](https://doi.org/10.1148/radiol.2433061165)
 22. Stolzmann P, Scheffel H, Schertler T, Frauenfelder T, Leschka S, Husmann L, Flohr TG, Marincek B, Kaufmann PA, Alkadhi H (2008) Radiation dose estimates in dual-source computed tomography coronary angiography. *Eur Radiol* 18:592–599. doi:[10.1007/s00330-007-0786-8](https://doi.org/10.1007/s00330-007-0786-8)
 23. Horiguchi J, Yamamoto H, Akiyama Y, Marukawa K, Hirai N, Ito K (2004) Coronary artery calcium scoring using 16-MDCT and a retrospective ECG-gating reconstruction algorithm. *AJR Am J Roentgenol* 183:103–108
 24. Kalender WA, Wolf H, Suess C, Gies M, Greess H, Bautz WA (1999) Dose reduction in CT by on-line tube current control: principles and validation on phantoms and cadavers. *Eur Radiol* 9:323–328. doi:[10.1007/s0033000050674](https://doi.org/10.1007/s0033000050674)
 25. Menzel H, Schibilla H, Teunen D (eds) (2000) European guidelines on quality criteria for computed tomography. *Luxembourg: European Commission*; Publication No. EUR 16262 EN
 26. Gerber TC, Kuzo RS, Morin RL (2005) Techniques and parameters for estimating radiation exposure and dose in cardiac computed tomography. *Int J Cardiovasc Imaging* 21:165–176. doi:[10.1007/s10554-004-5338-6](https://doi.org/10.1007/s10554-004-5338-6)
 27. McNitt-Gray MF (2002) AAPM/RSNA physics tutorial for residents: topics in CT. Radiation dose in CT. *Radiographics* 22:1541–1553. doi:[10.1148/rg.226025128](https://doi.org/10.1148/rg.226025128)
 28. Hausleiter J, Meyer T, Hadamitzky M, Huber E, Zankl M, Martinoff S, Kastrati A, Schomig A (2006) Radiation dose estimates from cardiac multislice computed tomography in daily practice: impact of different scanning protocols on effective dose estimates. *Circulation* 113:1305–1310. doi:[10.1161/CIRCULATIONAHA.105.602490](https://doi.org/10.1161/CIRCULATIONAHA.105.602490)
 29. Ohnesorge B, Flohr T, Fischbach R, Kopp AF, Knez A, Schroder S, Schopf UJ, Crispin A, Klotz E, Reiser MF, Becker CR (2002) Reproducibility of coronary calcium quantification in repeat examinations with retrospectively ECG-gated multisection spiral CT. *Eur Radiol* 12:1532–1540. doi:[10.1007/s00330-002-1394-2](https://doi.org/10.1007/s00330-002-1394-2)
 30. Ropers D, Baum U, Pohle K, Anders K, Ulzheimer S, Ohnesorge B, Schlundt C, Bautz W, Daniel WG, Achenbach S (2003) Detection of coronary artery stenoses with thin-slice multi-detector row spiral computed tomography and multiplanar reconstruction. *Circulation* 107:664–666. doi:[10.1161/01.CIR.0000055738.31551.A9](https://doi.org/10.1161/01.CIR.0000055738.31551.A9)
 31. van Ooijen PM, Vliegenthart R, Witteman JC, Oudkerk M (2005) Influence of scoring parameter settings on Agatston and volume scores for coronary calcification. *Eur Radiol* 15:102–110. doi:[10.1007/s00330-004-2479-x](https://doi.org/10.1007/s00330-004-2479-x)
 32. Van Hoe LR, De Meerleer KG, Leyman PP, Vanhoenacker PK (2003) Coronary artery calcium scoring using ECG-gated multidetector CT: effect of individually optimized image-reconstruction windows on image quality and measurement reproducibility. *AJR Am J Roentgenol* 181:1093–1100
 33. Groen JM, Greuter MJ, Schmidt B, Suess C, Vliegenthart R, Oudkerk M (2007) The influence of heart rate, slice thickness, and calcification density on calcium scores using 64-slice multidetector computed tomography: a systematic phantom study. *Invest Radiol* 42:848–855
 34. Kalra MK, Maher MM, Toth TL, Hamberg LM, Blake MA, Shepard JA, Saini S (2004) Strategies for CT radiation dose optimization. *Radiology* 230:619–628. doi:[10.1148/radiol.2303021726](https://doi.org/10.1148/radiol.2303021726)
 35. Gerber TC, Stratmann BP, Kuzo RS, Kantor B, Morin RL (2005) Effect of acquisition technique on radiation dose and image quality in multidetector row computed tomography coronary angiography with submillimeter collimation. *Invest Radiol* 40:556–563. doi:[10.1097/01.rli.0000170628.69792.cb](https://doi.org/10.1097/01.rli.0000170628.69792.cb)
 36. Sigal-Cinqualbre AB, Hennequin R, Abada HT, Chen X, Paul JF (2004) Low-kilovoltage multi-detector row chest CT in adults: feasibility and effect on image quality and iodine dose. *Radiology* 231:169–174. doi:[10.1148/radiol.2311030191](https://doi.org/10.1148/radiol.2311030191)
 37. Thomas CK, Muhlenbruch G, Wildberger JE, Hohl C, Das M, Gunther RW, Mahnken AH (2006) Coronary artery calcium scoring with multislice computed tomography: in vitro assessment of a low tube voltage protocol. *Invest Radiol* 41:668–673. doi:[10.1097/01.rli.0000233324.09603.dd](https://doi.org/10.1097/01.rli.0000233324.09603.dd)
 38. Mahnken AH, Wildberger JE, Simon J, Koos R, Flohr TG, Schaller S, Gunther RW (2003) Detection of coronary calcifications: feasibility of dose reduction with a body weight-adapted examination protocol. *AJR Am J Roentgenol* 181:533–538