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ORIGINAL RESEARCH

Image Quality and Radiation Exposure With Prospectively ECG-Triggered Axial Scanning for Coronary CT Angiography

The Multicenter, Multivendor, Randomized PROTECTION-III Study

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OBJECTIVES The purpose of this study was to evaluate image quality and radiation dose using a prospectively electrocardiogram (ECG)–triggered axial scan protocol compared with standard retrospective ECG-gated helical scanning for coronary computed tomography angiography.

BACKGROUND Concerns have been raised regarding radiation exposure during coronary computed tomography angiography. Although the use of prospectively ECG-triggered axial scan protocols may effectively lower radiation dose compared with helical scanning, it is unknown whether image quality is maintained in a clinical setting.

METHODS In a prospective, multicenter, multivendor trial, 400 patients with low and stable heart rates were randomized to either an axial or a helical coronary computed tomography angiography scan protocol. The primary endpoint was to demonstrate noninferiority in image quality with the axial scan protocol, which was assessed on a 4-point scale (1 = nondiagnostic, 4 = excellent image quality). Secondary endpoints included radiation dose and the rate of downstream testing during 30-day follow-up.

RESULTS Image quality in patients scanned with the axial scan protocol (score 3.36 ± 0.59) was not inferior compared with helical scan protocols (3.37 ± 0.59) (p for noninferiority $<$0.004). Axial scanning was associated with a 69% reduction in radiation exposure (dose-length product [estimated effective dose] 252 ± 147 mGy · cm [3.5 ± 2.1 mSv] vs. 802 ± 419 mGy · cm [11.2 ± 5.9 mSv] for axial vs. helical scan protocols, p $<$ 0.001). The rate of downstream testing did not differ (13.8% vs. 15.9% for axial vs. helical scan protocols, p = 0.555).

CONCLUSIONS In patients with stable and low heart rates, the prospectively ECG-triggered axial scan protocol maintained image quality but reduced radiation exposure by 69% compared with helical scanning. Axial computed tomography data acquisition should be strongly recommended in suitable patients to avoid unnecessarily high radiation exposure. (Prospective Randomized Trial on Radiation Dose Estimates of CT Angiography in Patients Scanned With a Sequential Scan Protocol [PROTECTION-III]; NCT00612092) (J Am Coll Cardiol Img 2012;5:484–93) © 2012 by the American College of Cardiology Foundation

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Coronary computed tomography angiography (CTA) has emerged as a useful diagnostic imaging modality for the noninvasive assessment of coronary artery disease with accepted clinical indications in selected patient groups (1). Although coronary CTA has high diagnostic performance to detect and exclude obstructive coronary artery disease (2–4), there are concerns regarding potential stochastic risks related to its use of ionizing radiation (5). Accordingly, strategies to obtain diagnostic images on coronary CTA with the lowest possible radiation exposure need to be developed and validated before they can be widely applied. In a recent randomized study, we demonstrated that coronary CTA imaging with a reduced tube potential of 100 kVp in nonobese patients preserves image quality compared with standard 120-kVp computed tomography (CT) data acquisition, while the estimated effective radiation dose is significantly reduced with 100-kVp imaging (6). However, it is critically important to appropriately balance the desire to achieve low radiation doses with the likelihood of obtaining a useful diagnostic image.

Prospective electrocardiogram (ECG)–triggered axial scanning, also known as "step-and-shoot" or "sequential scan mode" (7), has been introduced as an alternative scanning technique to standard helical (spiral) scanning with retrospective electrocardiographic gating with the intent to decrease coronary radiation dose on CTA. With this technique, radiation is applied only at a pre-defined point in the cardiac cycle, rather than during the entire cycle, which may reduce radiation exposure by approximately 60% to 80% (8–11). Although its use has been increasingly advocated (12–15), the comparative effect of coronary CTA using axial versus helical CT data acquisition on image interpretability, image quality, and radiation dose in consecutive adult patients has not been well established. Consequently, the primary objective of this randomized study was to demonstrate the noninferiority of an axial scan protocol for coronary CTA in terms of image quality compared with conventional helical scanning. The secondary objectives were to compare radiation doses and the need for additional downstream testing in the 2 groups.

METHODS

Study protocol. PROTECTION-III (Prospective Randomized Trial on Radiation Dose Estimates of Cardiac CT Angiography in Patients Scanned With an Axial Scan Protocol) is an international, multicenter, investigator-driven study, which randomized patients undergoing clinically indicated coronary CTA for suspected coronary artery disease at 9 study sites to either prospectively ECG-triggered axial or retrospectively ECG-gated helical data acquisition. Only patients in stable sinus rhythm with heart rates <65 beats/min scanned on single-source CT systems or heart rates <75 beats/min scanned on dual-source CT system were eligible for this study. Exclusion criteria were known coronary artery disease, extensive coronary artery calcifications with an Agatston score equivalent of >800 U (if calcium scoring had been performed), cardiac CTA for a noncoronary indication, and non–ECG-triggered or non–ECG-gated coronary CTA studies. The study protocol was approved by the local ethics committees. Written informed consent was obtained from each patient before enrolment in the study.

ABBREVIATIONS AND ACRONYMS

BMI = body mass index
CT = computed tomography
CTA = computed tomography angiography
DLP = dose-length product
ECG = electrocardiogram

Study design and coronary CTA. Patients were randomly assigned to an axial or a helical scan protocol by means of sealed envelopes. Separate randomization blocks were used for the participating institutions to allow for a comparable number of patients for each CT manufacturer. At 9 participating study sites, the following CT systems were used: LightSpeed VCT (2 sites; GE Healthcare, Milwaukee, Wisconsin), Brilliance 64 (3 sites; Philips Medical Systems, Best, the Netherlands) and Brilliance iCT (1 site; Philips Medical Systems), and Somatom Definition (3 sites; Siemens Medical Solutions, Forchheim, Germany).

The administration of beta-blockers was recommended to obtain heart rates lower than 60 beats/min. Coronary vasodilatation with the use of oral nitrates was also recommended. Before randomiza-

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tion, a localizer was acquired for planning of subsequent scan ranges, and, if indicated, an unenhanced scan for coronary artery calcium scoring was performed. Coronary CTA was carried out with scanner settings and with the contrast injection protocols at the discretion of the local study investigator. Depending on local algorithms, tube current and potential were selected, and subsequently, randomization envelopes, which contained instructions regarding the scan protocol (axial or helical), were opened. The use of a reduced tube potential of 100 kVp was recommended in nonobese patients, defined as either a body weight <90 kg or a body mass index (BMI) <30 kg/m^2. The study protocol recommended leaving all other scan parameters unchanged. The use of other strategies for radiation dose reduction, including selection of tube potential, ECG-controlled modulation of the tube current in ECG-gated helical data acquisition, or a widening of the data acquisition window with axial scanning, also known as "padding," was recommended when appropriate and clinically indicated.

After data acquisition, the local study investigators reconstructed the axial images according to local protocols and as needed for clinical decision making. Image reconstruction parameters including the selection of the cardiac phase with the lowest motion, the applied reconstruction kernel, and technique were at the discretion of the investigator. The study protocol required that all available axial datasets, which had been reconstructed for clinical decision making, be sent to the study core lab for analysis of image quality.

Study endpoints. The primary endpoint of the study was image quality, assessed with an image quality grading score. Secondary endpoints included radiation dose and quantitative image quality parameters. Furthermore, the need for downstream testing (stress echocardiography, stress nuclear cardiac perfusion imaging, or stress magnetic resonance imaging) and invasive coronary angiography within 30 days after coronary CTA was assessed as clinical endpoint. The follow-up protocol after coronary CTA consisted of a telephone interview at 30 days.

Data analysis. Two experienced operators who were unaware of the assigned scan protocol evaluated all datasets in the coronary CTA core laboratory. The datasets were anonymized and analyzed in random order to avoid any bias. The datasets were evaluated using axial slices, multiplanar reformations, and thin-slab maximum-intensity projections. Image quality was determined on the basis of a 4-point grading system, which has been described in detail elsewhere (6). In brief, each coronary artery (left main, left anterior descending, left circumflex, and right) was assigned a score of 1 (nondiagnostic image quality), 2 (adequate image quality), 3 (good image quality), or 4 (excellent image quality) by 2 experienced observers. To avoid intrapatient correlations, image quality scores of the 4 coronary arteries were averaged. In case of disagreement between the 2 observers, final assessment was made by an experienced third reader. In addition, coronary CTA studies with assigned scores of 1 in any coronary artery were defined as nondiagnostic studies. Pre-specified subgroup analyses for image quality scores were performed for: 1) patients in the fourth heart rate quartile; 2) patients with heart rates ≥65 beats/min; and 3) CT systems and manufacturers.

Coronary artery contours were assessed using a modified "blurring score" on a per patient basis (16). Using a 4-point scale, this score reflects the ability of coronary plaque assessment that could be hampered by graininess (mottle) and/or motion artifacts (Fig. 1): 1 = extensive blurring (reliable assessment of vessels contours impossible); 2 = medium blurring (graininess or motion impairing assessment of vessel contours but still containing sufficient informative value); 3 = slight blurring (minor blurring and/or graininess of the vessel contours); and 4 = minimal or no blurring (images with sharp vessel contours and little graininess).

Signal intensity, image noise, signal-to-noise ratio, and contrast-to-noise ratio were quantified as objective image quality parameters. All measurements were performed on reformatted axial images with a slice thickness of 1.0 mm to allow comparable measurements between different CT systems. Signal intensity was derived from the mean CT attenuation values (Hounsfield units) averaged from 2 circular regions of interest (size > 7 mm^2) in the proximal segments of the left and right coronary artery lumen. Image noise was defined as the averaged standard deviations of the CT attenuation values within these two regions of interest. The signal-to-noise ratio was calculated as the mean CT attenuation values of the left and right coronary arteries divided by the image noise. The contrast-to-noise ratio was defined as the difference between the mean CT attenuation values of the proximal coronary arteries and the mean density of the left lateral ventricular wall, which was divided by image noise.

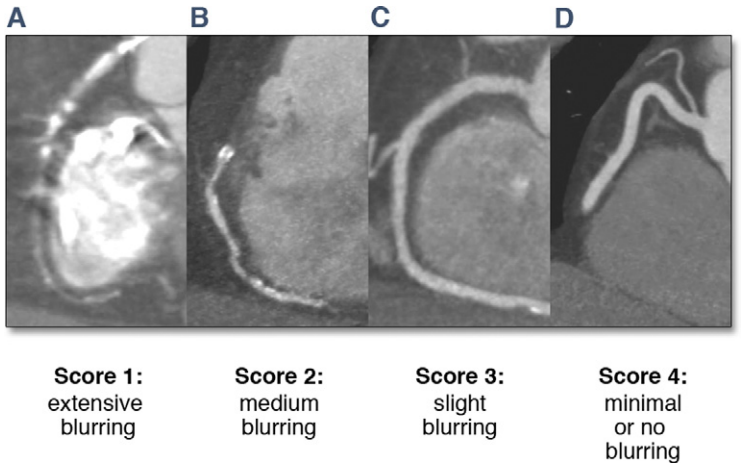

Figure 1. Examples of Different Blurring Scores

Representative examples for the different blurring scores. The examples show curved multiplanar reformations of the right coronary arteries of different patients. **(A)** Extensive blurring, **(B)** medium blurring, **(C)** slight blurring, and **(D)** minimal or no blurring.

Estimation of radiation dose. The study investigators obtained the parameters relevant to radiation dose, including volume CT dose index and dose-length product (DLP) from the scan protocol generated by the CT system after each coronary CTA study. The effective dose of coronary CTA can be estimated by a method proposed by the European Working Group for Guidelines on Quality Criteria in CT (17). The effective dose is derived from the product of the DLP and an organ-weighting factor for the chest as the investigated anatomic region. This organ-weighting factor ($k = 0.014$ $mSv \cdot mGy^{-1} \cdot cm^{-1}$) is averaged between male and female models. This weighting factor is considered to be derived from the most self-consistent and reliable dataset (18).

Statistical analysis. The objective of the study was to assess the noninferiority of an axial compared with a helical scan protocol. Sample size calculation was based on a margin of noninferiority for image quality score set at −0.20, because a larger difference has been considered clinically relevant (6). The assumed common standard deviation of image quality was 0.65. With power of 80% and a 2-sided alpha level of 0.05, we estimated that 167 patients in both groups were needed to show the noninferiority of the axial scan protocol. To compensate for unforeseeable scanning problems, we aimed to enroll a total of 400 patients (200 in each treatment arm). Sample size calculation was performed with nQuery Advisor (Statistical Solutions, Cork, Ireland). The analysis of primary and secondary endpoints was planned to be performed on an intention-to-diagnose basis. Results are expressed as counts (or proportions in percents) or as mean ± SD. Continuous and categorical variables were analyzed using 2-sided *t* tests and chi-square tests as appropriate. Differences in radiation dose were analyzed using the ordinal Wilcoxon rank sum test. The R language (R Project for Statistical Computing, Vienna, Austria) was used for statistical analyses. Statistical significance was defined as a p value <0.05. For subgroup analysis between CT system manufacturers, a Bonferroni adjustment was made for multiple comparisons, with a significance level of 0.0125.

RESULTS

Patient and coronary CTA characteristics. A total of 400 patients were enrolled between May 2008 and June 2009 at 9 participating institutions: 200 patients each were randomized to an axial or a helical scan protocol. Patient and coronary CTA characteristics are shown in Table 1. With an average body weight of 75.2 ± 14.8 kg and an average height of 1.70 ± 0.10 m, the mean BMI was 25.9 ± 3.8 kg/m^2. Both groups were well matched regarding the CT systems and manufacturers used and the administration of oral or intravenous beta-blockers before coronary CTA. The resulting heart rates were low during CT data acquisition, demonstrating a small but significant difference in favor of axial scanning (53.9 ± 6.1 beats/min vs. 55.6 ± 5.5 beats/min for axial vs. helical scanning, $p = 0.003$). There were no significant

Table 1. Patient and Coronary CTA Characteristics

	Axial (n = 200)	Helical (n = 200)	p Value
Height (m)	1.70 ± 0.10	1.69 ± 0.10	0.369
Weight (kg)	75.5 ± 14.3	75.0 ± 15.4	0.727
Body mass index (kg/m^2)	25.9 ± 3.4	26.0 ± 4.1	0.761
Beta-blocker administration before coronary CTA			0.488
None	46 (23.0)	41 (20.5)	
Oral	96 (48.0)	90 (45.0)	
Intravenous	58 (29.0)	69 (34.5)	
Heart rate (beats/min)	53.9 ± 6.1	55.6 ± 5.5	0.003
Scan length (mm)	135 ± 18	127 ± 28	0.002
CT system			0.859
GE	63 (31.5)	62 (31.0)	
Philips	69 (34.5)	74 (37.0)	
Siemens	68 (34.0)	64 (32.0)	
100-kVp tube potential	67 (33.5)	63 (31.5)	0.669

Values are mean ± SD or n (%).
CT = computed tomography; CTA = computed tomography angiography.

differences between the groups in the use of a reduced tube potential of 100 kVp, which was used in 33.5% and 31.5% of patients scanned with axial and helical data acquisition, respectively (p = 0.669). The scan length was 8 mm shorter with helical scanning (135 ± 18 mm vs. 127 ± 28 mm for axial vs. helical scanning, p = 0.002).

Coronary CTA image quality. The mean image quality score was 3.36 ± 0.59 in the cohort scanned with prospectively ECG-triggered axial acquisition and 3.37 ± 0.59 in patients scanned with retrospectively ECG-gated helical acquisition (p = 0.866) (Fig. 2A). Diagnostic noninferiority of the axial scan protocol was demonstrated because the lower margin or the 2-sided 95% confidence interval of −0.11 of the difference between image quality scores did not cross the pre-defined noninferiority margin of −0.2 score points (p = 0.004). Representative examples of 2 coronary CT angiograms acquired with axial and helical scanning are shown in Figures 3A (axial) and 3B (helical).

Nondiagnostic coronary CTA studies (image quality score of 1 in any coronary artery) were observed in 13.0% and 11.5% of axial and helical scans, respectively (p = 0.647). Motion artifacts were the leading reason for a nondiagnostic image quality score (Table 2). In these patients, heart rates were slightly higher than in patients with diagnostic coronary CTA image quality (56.4 ± 6.6 beats/min vs. 54.5 ± 5.7 beats/min for patients with nondiagnostic vs. diagnostic coronary CTA image quality, p = 0.028). Misalignment artifacts (1% and 0.5% for axial and helical, respectively) and extensive coronary calcifications (2% and 1% for axial and helical, respectively) were less frequently identified as reasons for nondiagnostic image quality. Results for quantitative image quality parameters, including the blurring score, are summarized in Table 2.

In pre-specified subgroup analyses, no significant differences in image quality grading scores were observed between axial and helical scan techniques in patients in the fourth quartile of heart rates (≥58 beats/min; 3.26 ± 0.67 vs. 3.12 ± 0.66 for axial vs. helical scans, p = 0.317). Only 21 patients with heart rates ≥65 beats/min were scanned; in these patients, no significant differences in image quality scores were seen between axial and helical scan techniques (3.22 ± 0.52 vs. 2.92 ± 0.70 for axial vs. helical scans, p = 0.287). Similarly, no significant differences in image quality grading score were

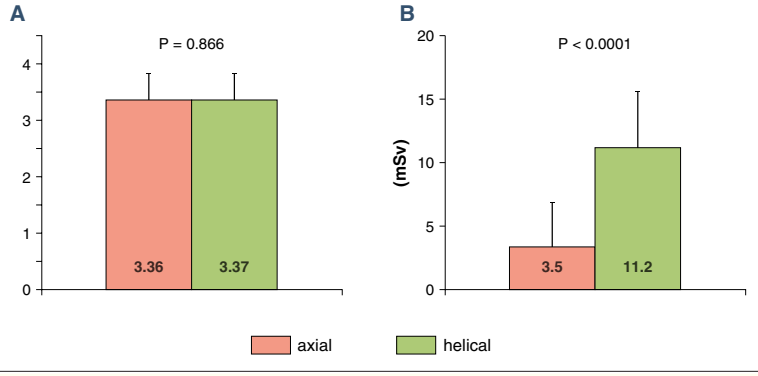

Figure 2. Image Quality Score and Estimated Radiation Dose

(A) Image quality score and **(B)** estimated effective radiation dose in the prospectively electrocardiogram-triggered axial and the retrospectively electrocardiogram-gated helical coronary computed tomography angiography scan groups.

observed between the different CT systems and manufacturers (Fig. 4A). Finally, no significant differences in image quality grading scores were observed between axial and helical scan techniques between nonobese and obese patients (BMI < 30 kg/m^2: 3.37 ± 0.59 vs. 3.40 ± 0.57 for axial vs. helical scans, $p = 0.593$; BMI ≥ 30 kg/m^2: 3.28 ± 0.59 vs. 3.20 ± 0.69 for axial vs. helical scans, $p = 0.658$).

Radiation exposure. Table 2 shows the results for radiation exposure with both scan protocols. The mean volume CT dose index was significantly lower for the axial scan protocol (18.6 ± 13.1 mGy) than for the helical scan protocol (53.5 ± 28.6 mGy) ($p < 0.0001$). Similarly, the DLP was significantly lower for the axial scan protocol (252 ± 147 mGy · cm vs. 802 ± 419 mGy · cm for axial vs. helical scanning, $p < 0.0001$). This corresponds to a 69% reduction in estimated effective radiation dose for the axial scan protocol (3.5 ± 2.1 mSv vs. 11.2 ± 5.9 mSv for axial vs. helical scan protocols) (Fig. 2B).

In a subgroup analysis of patients scanned with a 100-kVp scan protocol, DLP and estimated effective dose were reduced by 72% with axial scanning (DLP 160 ± 91 mGy · cm vs. 564 ± 280 mGy · cm; effective dose 2.2 ± 1.3 mSv vs. 7.9 ± 3.9 mSv for axial vs. helical scanning, $p < 0.0001$ for both). Radiation dose was reduced by 68% and 70% in nonobese and obese patients, respectively (DLP: BMI <30 kg/m^2, 250 ± 148 mGy · cm vs. 782 ± 404 mGy · cm for axial vs. helical scans, $p < 0.0001$, and BMI ≥ 30 kg/m^2, 267 ± 138 mGy · cm vs. 900 ± 480 mGy · cm for axial vs. helical scans, $p < 0.0001$). Radiation dose reductions with axial scanning as stratified by different CT systems and manufacturers are displayed in Figure 4B.

Clinical follow-up. Thirty-day clinical follow-up was completed in 97.8% of patients. During follow-up, 27 patients of the axial scan group underwent additional testing for suspected obstructive coronary artery disease (26 patients with invasive coronary angiography, 1 patient with stress nuclear cardiac perfusion imaging, and 1 patient with stress echocardiography). In the helical scan group, 31 patients subsequently underwent additional tests; all patients were studied using invasive coronary angiography. Consequently, the rate of downstream testing did not differ significantly between both groups (13.8% vs. 15.9% for axial vs. helical scanning, $p = 0.555$). No significant differences in image quality score were observed between patients with and without need for additional diagnostic testing (with additional diagnostic testing, 3.40 ± 0.46 vs. 3.27 ± 0.54, $p = 0.354$; without additional diagnostic testing, 3.36 ± 0.61 vs. 3.39 ± 0.60, $p = 0.608$) for axial versus helical scans, respectively.

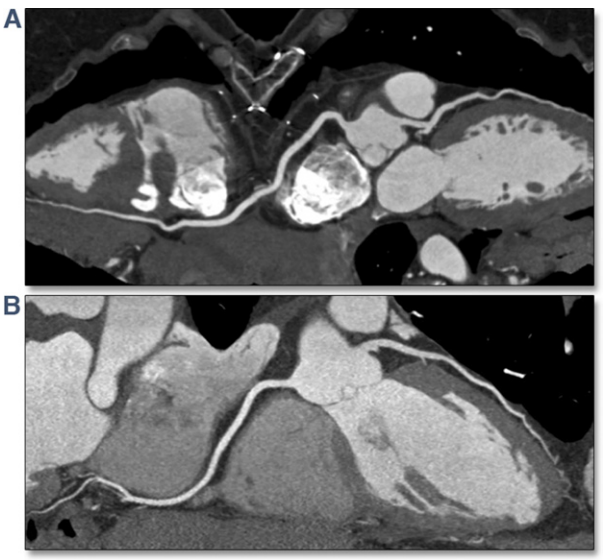

Figure 3. Curved Multiplanar Reformations

(A) Coronary computed tomography angiography (CTA) acquired with prospectively electrocardiogram-triggered axial data acquisition in a patient (height 164 cm, weight 70 kg, heart rate 47 beats/min) on a Siemens Definition scanner. Applying a tube voltage of 120 kV and tube current of 371 ref.mAs, the resulting dose-length product was 257 mGy · cm (estimated effective dose 3.6 mSv). **(B)** Coronary CTA acquired with retrospectively electrocardiogram-gated helical data acquisition in a patient (height 177 cm, weight 83 kg, heart rate 53 beats/min) on a Siemens Definition scanner. Applying a tube voltage of 100 kV and tube current of 360 ref.mAs, the resulting dose-length product was 288 mGy · cm (estimated effective dose 4.0 mSv).

Table 2. Results on Image Quality and Radiation Exposure

	Axial (n = 200)	Helical (n = 200)	p Value
Image quality score	3.36 ± 0.59	3.37 ± 0.59	0.866
Nondiagnostic image quality due to			0.203
Motion	16 (8.0)	20 (10.0)	
Excessive calcification	4 (2.0)	2 (1.0)	
Stair step artifacts	5 (2.5)	1 (0.5)	
Others	1 (0.5)	0 (0.0)	
Blurring score	2.77 ± 0.78	2.71 ± 0.83	0.452
Signal intensity (HU)	412 ± 122	412 ± 113	0.969
Image noise (HU)	27.7 ± 15.2	24.7 ± 17.6	0.073
Signal-to-noise ratio	17.3 ± 7.7	19.0 ± 7.4	0.021
Contrast-to-noise ratio	13.0 ± 6.5	14.4 ± 6.2	0.025
$CTDI_{vol}$ (mGy)	18.6 ± 13.1	53.5 ± 28.6	<0.0001
DLP (mGy · cm)	252 ± 147	802 ± 419	<0.0001
Effective dose estimate (mSv)	3.5 ± 2.1	11.2 ± 5.9	<0.0001

Values are mean ± SD or n (%).
$CTDI_{vol}$ = volume computed tomographic dose index; DLP = dose-length product; HU = Hounsfield units.

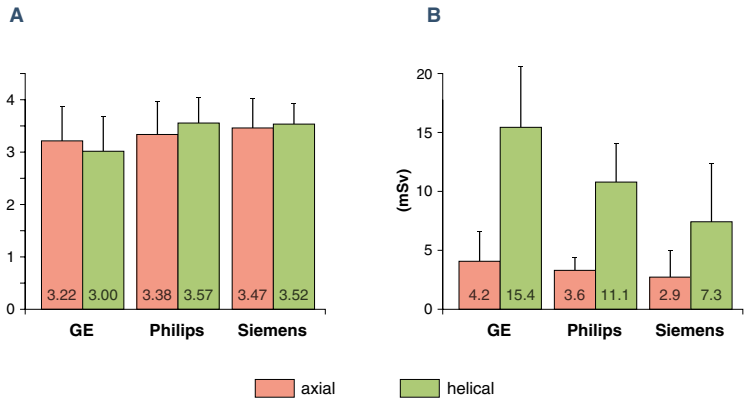

Figure 4. Image Quality Score and Radiation Dose for Different CT Vendors and Systems

(A) Image quality score (all p = n.s.) and **(B)** estimated effective radiation dose (all p < 0.001) in the prospectively electrocardiogram-triggered axial and the retrospectively electrocardiogram-gated helical coronary computed tomography angiography scan groups displayed according to the computed tomography (CT) system manufacturer. The study included predominantly 64-slice CT systems; GE and Philips CT scanners used a single-source configuration, while a dual-source configuration was used with Siemens CT systems.

DISCUSSION

Within the past few years, a variety of strategies have been proposed to reduce exposure to ionizing radiation during coronary CTA, including automated exposure control (19), ECG-controlled tube current modulation (20), and the use of a reduced tube potential of 100 kVp (21). It is important that the use of reduced dose acquisition protocols not increase the rate of nondiagnostic studies. This has been demonstrated for some dose reduction strategies, such as the use of a reduced tube potential. For example, we were able to demonstrate in a prior study that 100-kVp imaging in nonobese patients was associated with comparable graded image quality, and similar rates of downstream testing, while radiation exposure was reduced by 31% compared with conventional 120-kVp imaging (6). The study presented here provides further support that coronary CTA with lower radiation dose is feasible without compromising diagnostic image quality, when the prospectively ECG-triggered axial scan mode is used. In retrospectively ECG-gated helical scanning, x-ray data are acquired throughout the entire cardiac cycle with a continuous rotation of the gantry and simultaneous movement of the patient table. With axial scanning, radiation exposure and therefore CT data acquisition are initiated after the detection of an R peak and are limited to only a pre-defined phase of the cardiac cycle, usually the diastolic phase with greatest likelihood of minimal cardiac motion. Radiation exposure is then suspended while the patient table is moved to the next z-axis position, and the process is repeated until the entire scan length is covered. In this prospective randomized study, we compared both scan protocols, axial and helical, concerning image quality in patients with suspected coronary artery disease. We demonstrated that the use of an axial scan technique for coronary CTA resulted in comparable and noninferior image quality compared with conventional helical scanning, while at the same time the estimated radiation dose was reduced by 69%. Furthermore, the ability of coronary plaque assessment as determined by the contour blurring score was comparable between both groups. These findings were consistently observed across multiple manufacturers and platforms, implying that these results may be generalizable to a variety of commercially available CT scanners. Furthermore, the study identified similarly low rates of downstream testing, suggesting that the use of the axial scan protocol was not associated with an increased near-term repeat testing or resource utilization.

The reduction in radiation dose with prospectively ECG-triggered axial scanning was incremental to other dose reduction techniques. The mean DLP in nonobese patients scanned with a tube potential of 100 kVp was only 160 ± 91 mGy · cm, which corresponds to an estimated effective dose of only 2.2 ± 1.3 mSv. This finding suggests that the use of the prospective ECG-triggered axial scan technique may be effective in comprehensive dose reduction strategies.

The present study did not compare the diagnostic accuracy of prospectively ECG-triggered axial with retrospectively ECG-gated helical scanning. As

shown previously (6), such a study would require the enrollment of an unrealistically large number of patients. However, numerous smaller single-center studies have studied the diagnostic accuracy of prospectively ECG-triggered axial scanning (13–15). A recent meta-analysis included 16 of those studies, with a total of 960 patients (22). The average BMI was 26.5 kg/m^2, and the average heart rate was 57.5 beats/min, which are both slightly higher than in the present study. This meta-analysis revealed high sensitivity and specificity values of 100% (95% confidence interval: 98% to 100%) and 89% (95% confidence interval: 85% to 92%) in the per patient analysis, with an average estimated effective radiation dose of 2.7 mSv (95% confidence interval: 2.2 to 3.2 mSv) for the prospectively ECG-triggered axial scan technique.

With the prospectively ECG-triggered axial scan technique, the minimum duration of radiation exposure is approximately one-half the gantry rotation time plus the fan angle for single-source CT scanners. This limits visualization of the coronary arteries to a single, pre-specified time point of the cardiac cycle, usually in mid-diastole. If multiple phases of the cardiac cycle are needed for the assessment of the coronary arteries, the duration of radiation exposure can be prolonged beyond the required minimum, which is also known as "padding." This technique may permit minor retrospective adjustments of the reconstruction window, potentially reducing cardiac motion artifacts. However, a recent multicenter study could not demonstrate improved image interpretability with "padding" in patients with low and stable sinus rhythm, while the radiation exposure was significantly increased (23). As a consequence, current guidelines recommend keeping the data acquisition window as short as possible (24). In the present study, the length of the data acquisition window, which was at the discretion of the CT imager, was not recorded, prohibiting us from performing further analyses of its impact on image quality grading scores.

As pointed out before, it is critically important to appropriately balance the desire to achieve low radiation exposures with the likelihood of obtaining useful diagnostic images. Too little radiation exposure for a given patient during coronary CTA may result in excessive image noise and unevaluable coronary arteries, while exuberant radiation exposure may improve aesthetic image quality with reduced image noise but without gain of additional diagnostic information. The present study demonstrates that the use of the prospectively ECG-triggered axial scan mode is associated with a favorable balance in obtaining highly diagnostic coronary CTA images with sharp arterial contours and acceptable noise levels, while radiation exposure is significantly reduced.

Patient inclusion was limited to patients in stable sinus rhythm with heart rates lower than 65 beats/min for single-source and lower than 75 beats/min for dual-source CT systems because of the higher temporal resolution of dual-source CT systems. Pre-specified subgroup analyses did not identify a deterioration of image quality with the prospectively ECG-triggered axial scan technique in the small group of patients scanned at higher heart rates. Although some newer scanner generations provide scan techniques allowing systolic and diastolic image reconstructions with axial scanning in patients with higher heart rates, further dedicated studies are needed to determine the image quality and diagnostic performance of the prospective ECG-triggered axial scan technique in patients with higher heart rates.

This study included patients with low to intermediate risk for having obstructive coronary artery disease. Although the image quality was also comparable between prospectively ECG-triggered axial and retrospectively ECG-gated helical scans in the subgroup of patients with suspected coronary artery disease undergoing additional diagnostic testing during follow-up, it remains unproven if the present study's results can be applied to patients at high risk for having coronary artery disease or patients with advanced stages of coronary atherosclerosis. The majority of CT systems used in this study were 64-slice scanners, and newer scanners with more detector rows as well as other radiation sparing techniques have become available. However, the investigated prospectively ECG-triggered axial scan protocol is also applicable on these newer scanners. In fact, current guidelines on radiation dose for coronary CTA recommend its use for all patients in stable sinus rhythm with low heart rates, irrespective of the CT scanner configuration (24).

CONCLUSIONS

The PROTECTION-III study demonstrates that image quality is maintained when using prospectively ECG-triggered axial scanning in patients with low and stable heart rates, while at the same time a 69% reduction in estimated radiation dose is achieved compared with retrospectively ECG-gated helical scanning. Consequently, the prospectively

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ECG-triggered axial scan technique should be used for coronary CTA in all patients with low and stable heart rates, in pursuit of the ultimate goal of obtaining diagnostic coronary CTA images with the lowest possible radiation dose.

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