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Radiation dose of coronary CT angiography with a third-generation dual-source CT in a "real-world" patient population

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Abstract

Objectives To assess radiation dose and image quality of coronary computed tomography angiography (cCTA) with a third-generation dual-source scanner in a real-world patient population.

Methods Scans of otherwise unselected, consecutive patients referred for clinically indicated cCTA between June 2015 and November 2017 were included for retrospective analysis. Scan protocol was based on heart rate: prospectively ECG-gated high-pitch spiral below 60 beats per minute (bpm), prospectively ECG-gated sequential scan between 61 and 70 bpm, and retrospective spiral above 70 bmp or at irregular heart rates. Objective image quality was measured as signal-to-noise (SNR) and contrast-to-noise ratio (CNR); subjective image quality was evaluated using a five-point Likert scale by two independent readers. For radiation dose analysis, effective dose, size-specific dose estimates, and volume CT dose index were assessed.

Results Two hundred seventy-eight patients (median age, 60 years; 155 men) with a median body mass index of 26.6 kg/m^2 (range, 16.7–60.9 kg/m^2; 180 (64.7%) overweight or obese) were included (122 in the high-pitch spiral group, 60 in the prospective sequence group, and 96 in the retrospective spiral group). Median effective dose was 0.63 mSv (interquartile range [IQR], 0.51–0.90 mSv) for high-pitch spiral, 1.32 mSv (IQR, 0.79–2.46 mSv) for prospective sequence, and 4.77 (IQR, 3.02–8.27 mSv) for retrospective spiral ($p < 0.001$). Most studies had at least very good image quality (91.4/88.8% R1/R2), with highest SNR and CNR in the high-pitch spiral group.

Conclusions cCTA with sufficient image quality is achievable at reasonably low radiation exposure in a real-world patient collective with a high proportion of overweight or obese patients.

Key Points

- *Submillisievert radiation dose coronary CT angiography with good diagnostic image quality is feasible in the majority of cases in a real-world patient using high-pitch spiral.*
- *Prospective sequence results in about double median effective dose compared to the high-pitch protocol.*
- *To optimize individual radiation exposure, lowering the heart rate is paramount, as it allows for choosing a dose-optimized (high-pitch spiral) scan protocol.*

Keywords Computed tomography angiography · Radiation dosage · Coronary artery disease · Heart rate · Body mass index

Abbreviations

CAD	Coronary artery disease
cCTA	Coronary computed tomography angiography
CNR	Contrast-to-noise ratio
CT	Computed tomography
$CTDI_{vol}$	Volume computed tomography dose index
DLP	Dose-length product
ECG	Electro cardiogram
ROI	Region of interest
SNR	Signal-to-noise ratio
SSDE	Size-specific dose estimates

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Introduction

Coronary computed tomography angiography (cCTA) is widely used and well established for non-invasive assessment of coronary artery disease (CAD) [1, 2] and often considered a preferred tool for diagnosis in patients with low-to-intermediate pretest probability of CAD [3–5]. It allows for a fast and highly sensitive evaluation of atherosclerotic changes and can be used as a reliable technique to exclude significant CAD in patients with acute chest pain due to its high negative predictive value [6–8]. Over the last decades, technological innovations and improved image acquisition protocols helped to increase diagnostic performance and reduce radiation exposure [9–11]. Especially the reduction of radiation dose is of paramount importance, as public concern about exposure to medical radiation and possible associated long-term risks is on the rise [12–15].

Previous studies showed that the introduction of the third-generation dual-source scanner with further improvements of X-ray tube technology, gantry rotation speed, detector coverage, pitch settings, and iterative reconstruction algorithms allows for a further reduction of radiation dose and contrast medium volume while maintaining or even improving image quality [16, 17]. Consequently, effective radiation dose could be minimized to values of less than 0.1 mSv in high-pitch spiral cCTA in a highly selected patient cohort [18]. Yet, in less selected patient cohorts, the amount of radiation exposure for different available scan protocols of cCTA with a contemporary third-generation dual-source CT remains unclear.

We hypothesized that also in a real-world population of consecutive patients, high-pitch cCTA will result in low radiation exposure compared to prospective sequential cCTA and retrospectively gated cCTA. Therefore, the purpose of this study was to test whether high-pitch cCTA results in lower radiation dose and similar image quality to prospective sequential and retrospectively gated cCTA in otherwise unselected, consecutive patients.

Methods

Patients

The institutional review board waived the need for approval or written informed consent for this single-center retrospective study. A total of 278 consecutive patients (mean age, 60 years; range, 18–83), including 155 men (mean age, 57 years; range, 18–80) and 123 women (mean age, 62 years; range 36–83) with low-to-intermediate risk of CAD referred for clinically indicated cCTA between June 2015 (establishment of scan protocols mentioned below) and November 2017 (start of retrospective data analysis) for diagnostic workup of suspected CAD were included. The timeframe was chosen to ensure a sufficient number of patients per group. Patient selection was solely chronological without any further inclusion or exclusion criteria. Of the 278 patients, 3 (1.1%) were underweight (BMI < 18.5 kg/m^2), 95 (34.2%) had normal weight (BMI 18.5–25 kg/m^2), 109 (39.2%) were overweight (BMI 25–30 kg/m^2), and 71 (25.5%) were obese (BMI > 30 kg/m^2).

Patients received 47.5 mg of metoprolol orally (MetoHEXAL®, Hexal) 60 min before the planned scan in the absence of contraindications. Additionally, just before acquisition of the CCS scan and the subsequent cCTA, all patients without contraindications received 0.8 mg of glyceryl trinitrate sublingually (Nitrolingual® akut Spray, Pohl-Boskamp).

Scan protocols

All scans were performed on a third-generation dual-source CT system (SOMATOM® Force, Siemens Healthineers). An unenhanced standard coronary calcium scoring (CCS) scan to obtain the Agatston scores was acquired before the cCTA in each patient. Scan length for the cCTA was optimized based on the anatomical information obtained with the CCS scan. Depending on the heart rate and rhythm during the CCS scan, cCTA was performed using one of the following protocols: in patients with a heart rate below 60 beats per minute (bpm), a prospectively electrocardiogram (ECG)-gated high-pitch spiral was acquired during the diastole of a single cardiac cycle; patients with a heart rate between 61 and 70 bmp received a prospectively ECG-gated sequential scan; and patients with a heart rate above 70 bmp or an irregular heart rate (variance above 10 bpm during a 30-s observation period) were scanned with a retrospectively ECG-gated spiral. Automatic exposure control based on topogram information was activated to enable the adjustment of tube voltage (CARE kV, Siemens Healthineers) and tube current (adjustment level: average; CARE Dose 4D, Siemens Healthineers). Padding and pulsing were deactivated for the prospective sequence and retrospectively ECG-gated protocol, respectively.

To achieve contrast enhancement, a bolus-tracking protocol with a threshold of 100 Hounsfield units (HU) within a circular region of interest (ROI) placed in the ascending aorta was used. Scan delay was set to 10/5/6 s for the high-pitch spiral/prospective sequence/retrospective spiral protocol, respectively. In all patients, 60 ml of contrast medium (Ultravist, 370 mg/ml iodine, Bayer Vital) followed by a 40 ml saline chaser was injected at a flow rate of 5 ml/s through an 18-gauge intravenous antecubital catheter.

Image reconstruction and evaluation

Unenhanced calcium scoring data was reconstructed with a slice thickness of 3 mm with a Qr36 kernel. The calcium score was determined using dedicated software (syngo via, Siemens Healthineers) following the Agatston method [19]. cCTA data was reconstructed with a slice thickness of 0.6 mm in the axial plane (increment, 0.3 mm). Advanced modeling iterative

Table 1 Patient demographics

Parameters	Calcium scoring	High-pitch spiral	Prospective sequence	Retrospective spiral	p value[a]
N	278	122	60	96	
Mean age (years)	60 ± 11	59 ± 11	59 ± 11	59 ± 12	0.99
No. of men (%)	155 (55.8)	75 (61.5)	31 (51.7)	49 (51.0)	0.24
Mean height (cm)	172 ± 10	173 ± 10	172 ± 10	171 ± 9	0.12
Median weight (kg)	80 (70–93)	80 (72–90)	81 (70–98)	80 (66–94)	0.90
Median body mass index (kg/m^2)	26.6 (24.0–30.0)	26.4 (24.5–29.6)	26.4 (24.1–31.1)	27.3 (23.3–30.6)	0.73
No. of underweight patients (< 18.5 kg/m^2)	3 (1.1)	2 (1.6)	1 (1.7)	0 (0.0)	
No. of patients of normal weight (18.5–25 kg/m^2)	95 (34.2)	41 (33.6)	19 (31.7)	35 (36.5)	
No. of overweight patients (25–30 kg/m^2)	109 (39.2)	54 (44.3)	22 (36.7)	33 (34.4)	
No. of obese patients (> 30 kg/m^2)	71 (25.5)	25 (20.5)	18 (30.0)	28 (29.2)	
Median effective diameter (cm)	30.9 (28.8–33.2)	30.8 (29.2–33.0)	30.7 (28.5–33.4)	30.9 (28.5–33.7)	0.86
Mean heart rate (beats/min)	64 ± 12	58 ± 9	66 ± 10	71 ± 16	
Median Agatston score	4.4 (0.0–120.7)	5.3 (0.0–62.3)	29.6 (0.0–254.1)	2.5 (0.0–180.0)	0.50

[a] For different cCTA protocols, calcium scoring excluded. Values provided as frequencies, means ± standard deviations, or medians and interquartile ranges (25/75)

reconstruction technique strength level 3 using a vascular kernel (Bv40) was applied.

Image evaluation was performed in a randomized fashion with dedicated software (syngo via, Siemens Healthineers). CT attenuation values (in HU) within circular ROIs at the level of the origin of the right coronary artery were recorded for the ascending aorta and paracardial fat by one reader (A.K.) with 5 years of experience in cCTA. These attenuation values were used to gain contrast-to-noise ratio (CNR) as described before [20]. Subjective image quality was evaluated independently by two observers (T.G. and A.K., with 7 and 5 years of experience in cCTA, respectively). Both readers independently assessed overall image quality on a per patient base using a five-point Likert scale: 1, not diagnostic, excessive artifacts, insufficient contrast; 2, moderate quality, distinct artifacts, little contrast, high noise; 3, good quality, moderate artifacts, sufficient contrast, moderate noise; 4, very good quality, minimal artifacts, good contrast, minimal noise; and 5, excellent quality, no artifacts, excellent contrast, limited perceived image noise.

Table 2 Scan parameters

Parameters	Calcium scoring	High-pitch spiral	Prospective sequence	Retrospective spiral	p value[a]
Reference kV	120	100	100	70	
Effective tube voltage					< 0.001
70 kVp (%)	0	12 (9.8)	26 (43.3)	49 (51.0)	
80 kVp (%)	0	59 (48.4)	11 (18.3)	23 (24.0)	
90 kVp (%)	0	37 (30.3)	8 (13.3)	12 (12.5)	
100 kVp (%)	0	11 (9.0)	0 (0.0)	10 (10.4)	
110 kVp (%)	0	2 (1.6)	0 (0.0)	1 (1.0)	
120 kVp (%)	278 (100)	1 (0.8)	15 (25.0)	1 (1.0)	
Qual. ref. mAs	80	288	280	320	
CARE dose 4D adjustment	Average	Average	Average	Average	
Gantry rotation time (s)	0.25	0.25	0.25	0.25	
Pitch	3.2	3.2	–	0.2	
Collimation	192 × 0.6 mm	192 × 0.6 mm	96–192 × 0.6 mm	192 × 0.6 mm	
Median scan length (cm)[a]	15.8 (14.6–17.0)	12.0 (10.9–13.4)	11.9 (11.1–13.2)	12.0 (10.8–13.2)	0.84
Delay (s)	–	10	5	6	

[a] For different cCTA protocols, calcium scoring excluded. Values provided as medians and interquartile ranges (25/75)

Table 3 Subjective image quality

Likert scale	High-pitch spiral		Prospective sequence		Retrospective spiral	
	R1	R2	R1	R2	R1	R2
5	90 (73.8)	90 (73.8)	33 (55.0)	33 (55.0)	75 (78.1)	69 (71.9)
4	24 (19.7)	18 (14.8)	15 (25.0)	16 (26.7)	17 (17.7)	21 (21.9)
3	6 (4.9)	10 (8.2)	10 (16.7)	6 (10.0)	4 (4.2)	5 (5.2)
2	1 (0.8)	2 (1.6)	2 (3.3)	5 (8.3)	–	1 (1.0)
1	1 (0.8)	2 (1.6)	–	–	–	–
Median	5	5	5	5	5	5

Values displayed as frequencies and relative percentage in parenthesis

Radiation dose assessment

The volume CT dose index ($CTDI_{vol}$) and the dose-length product (DLP) were recorded from the report automatically generated by the scanner. A conversion factor of 0.014 mSv/mGy•cm was used to estimate effective dose [21]. Due to differences in patient size and sex, the effective dose estimated based on a standard reference adult does not reflect an individual patient's dose. Hence, to account for differences in patient physique and obtain a more individualized measure of radiation exposure, size-specific dose estimates (SSDE) were calculated [22] based on effective patient diameter defined as the square root of the product of anterior-posterior and lateral thorax diameters at the level of the origin of the right coronary artery.

Statistical analysis

Statistical analyses were performed using dedicated software (SPSS Statistics version 23; IBM). Categorical variables are presented as frequencies and percentages. Normal distribution of continuous variables was evaluated by the Kolmogorov-Smirnov test. Normally distributed data are displayed as means ± standard deviation, otherwise as medians and interquartile ranges (25/75). Pearson's chi-squared test was used to evaluate proportions of categoric data. One-way ANOVA was used to compare continuous normally distributed variables, and the Kruskal-Wallis H Test was used to compare nonparametric variables. The interreader reliability for subjective image quality ratings was calculated with the intraclass correlation coefficient (two-way random effects model testing for consistency) and interpreted according to Koo et al [23]. Correlation between dose parameters and BMI was assessed using Spearman's correlation analysis. A p value ≤ 0.05 was considered statistically significant.

Results

Detailed patient population characteristics are provided in Table 1. There was no significant difference between patients for the three protocol subgroups in respect to number of men, mean height, median weight, BMI, effective diameter, or Agatston score. Average heart rate was 58 bpm in the high-pitch spiral group, 66 bpm in the prospective sequence, and 71 bpm in the retrospective spiral group. The CT scan parameters are summarized in Table 2. There was no significant difference with regard to scan length between the cCTA protocols.

Of all 278 cCTA scans, reader 1 rated only one high-pitch spiral scan as not diagnostic, and reader 2 rated two high-pitch spiral scans as not diagnostic, due to excessive artifacts or insufficient contrast, respectively. There were no non diagnostic scans in the other two scan protocols. The overall image quality was assessed as very good or excellent in 93.4/88.5% (R1/R2) of high-pitch spiral scans, 80.0/81.7% of the prospective sequence scans, and 95.8/93.8% for the retrospective spiral scans (Table 3). For both readers, the

Table 4 Objective image quality

Parameters	High-pitch spiral	Prospective sequence	Retrospective spiral	p value[a]
HU aorta	398 (317–490)	552 (378–755)	597 (464–735)	< 0.001
SD aorta	20.6 (15.4–34.0)	40.2 (22.1–55.3)	35.9 (29.4–53.2)	< 0.001
SNR	17.4 (12.2–24.2)	14.4 (9.5–20.6)	14.8 (11.4–19.1)	0.016
CNR	24.1 (15.6–31.0)	18.1 (11.6–25.7)	17.8 (14.1–23.1)	< 0.001

[a] For different coronary CT angiography protocols, calcium scoring excluded. Values provided as medians and interquartile ranges

Table 5 Radiation dose

Parameters	Calcium scoring	High-pitch spiral	Prospective sequence	Retrospective spiral	p value[a]
$CTDI_{vol}$ (mGy)	1.78 (1.42–2.17)	2.65 (2.23–3.90)	7.06 (4.73–15.03)	21.67 (14.14–37.38)	< 0.001
DLP (mGy × cm)	35.4 (28.3–43.9)	44.8 (36.6–64.6)	94.3 (56.4–175.9)	340.4 (215.6–590.4)	< 0.001
Effective dose (mSv)	0.50 (0.40–0.62)	0.63 (0.51–0.90)	1.32 (0.79–2.46)	4.77 (3.02–8.27)	< 0.001
SSDE (mGy)	2.14 (1.82–2.42)	3.12 (2.71–4.38)	8.30 (5.79–15.03)	26.18 (18.17–39.58)	< 0.001

[a] For different cCTA protocols, calcium scoring excluded. Values provided as medians and interquartile ranges (25/75)

subjective rating of image quality in the prospective sequence group proved to be significantly lower than in the high-pitch spiral and retrospective spiral group (R1, $p = 0.002$; R2, $p = 0.021$). Irrespective of scan protocol, the image quality was rated as very good or excellent in 91.4/88.8% (R1/R2) of the scans. Ordinal regression to investigate possible dependencies of the subjective image quality measures from applied technique and body mass index showed that subjective image quality ratings of both readers depend from the body mass index only, while the applied scan protocol turned out to be a non-significant predictor of the outcome. The single measure intraclass correlation coefficient for overall subjective image quality was 0.873 (95% confidence interval, 0.842–0.898; $p < 0.001$), indicating good to excellent interobserver reliability. Quantitative image analysis revealed significant differences in CNR and SNR between cCTA protocols, with highest CNR and SNR values in the high-pitch spiral group, and lowest in the prospective sequence group (Table 4). Highest median attenuation in the aorta was measured in the retrospective spiral group with 597 HU, followed by 552 HU in the prospective sequence group and 398 HU in the high-pitch spiral group.

$CTDI_{vol}$, DLP, effective dose, and SSDE varied significantly between the cCTA protocols, with highest values for the retrospective spiral and lowest for the high-pitch spiral, respectively (Table 5, Fig. 1). Correlation between radiation parameters and BMI for each cCTA protocol is shown in Fig. 2a–c.

Discussion

Our results show that in a real-world population of consecutive patients, cCTA is achievable with adequate diagnostic image quality at reasonably low radiation exposure using a third-generation dual-source CT with heart rate being the primary determinant of CT scan protocol. Despite a high overall proportion of overweight or obese patients, submillisievert radiation doses (median 0.63 mSv) were feasible for the high-pitch spiral in the vast majority of patients, with about double median effective dose (1.32 mSv) for the prospective sequence and eight times higher (4.77 mSv) median dose for the retrospective spiral.

Previous studies have shown that a reduction of kilovoltage settings from 120 to 100 kV in non-obese patients can lead to significantly lower radiation exposure [24–26]. Accordingly, current guidelines propose lowering tube voltage from 120 to 100 kV for non-obese patients [10]. After the introduction of third-generation dual-source scanners with improved X-ray tube technology resulting in higher tube output at lower tube voltages; however, tube currents of 80 kV or even 70 kV at acceptable noise levels became viable for clinical cCTA purposes. At low tube voltages, mean X-ray photon energy is closer to the k-edge of iodine, which increases the photoelectric effect and leads to higher vessel contrast, at cost of higher image noise due to inferior X-ray penetration [17, 27–31]. Several studies demonstrated a further reduction of radiation exposure during cCTA in non-obese patients using tube current settings

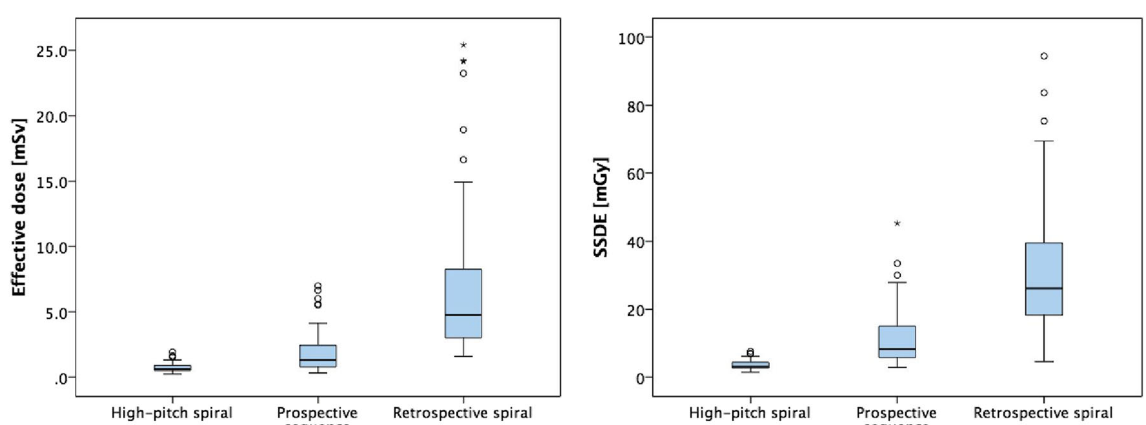

Fig. 1 Effective dose and SSDEs (size-specific dose estimates) for different coronary computed tomography angiography protocols

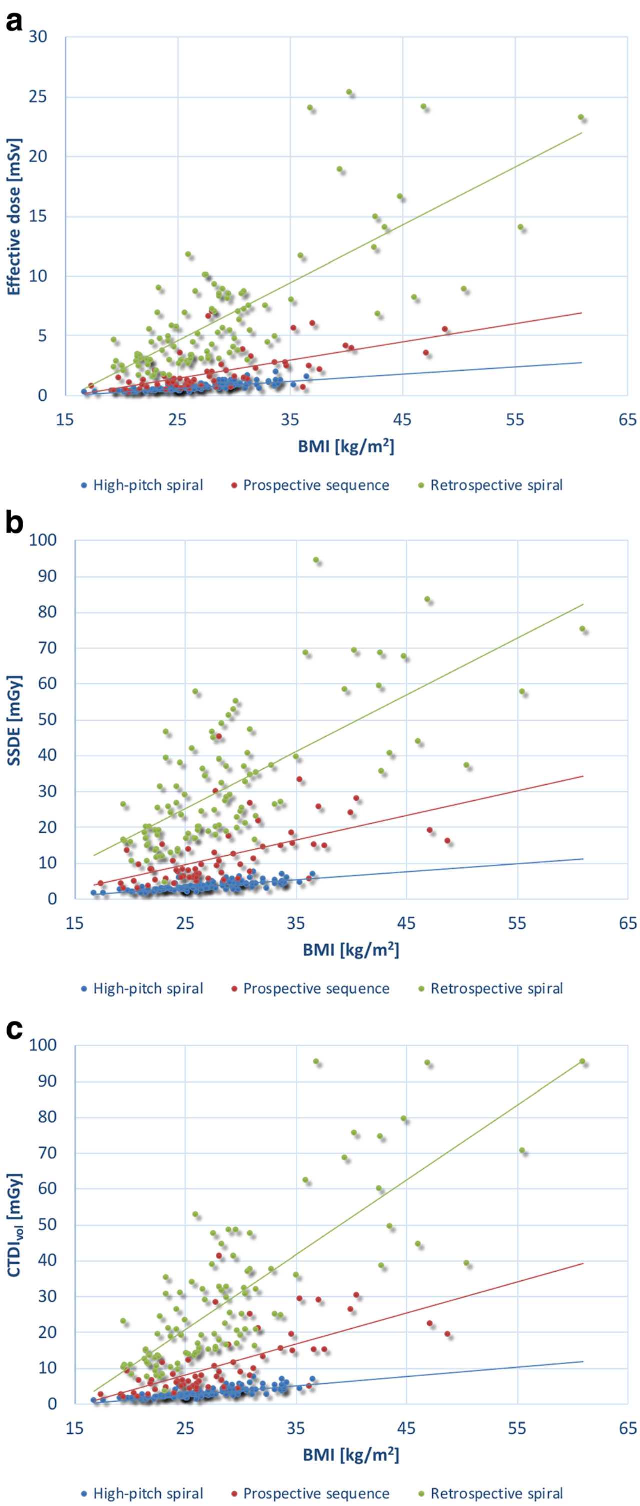

Figure 2 Correlations between effective dose (**a**), SSDEs (size-specific dose estimates) (**b**), and $CTDI_{vol}$ (volume computed tomography dose index) (**c**) and BMI (body mass index)

of 80 kV or 70 kV [17, 27, 28]. However, in daily clinical routine, a considerable amount of overweight or obese patients can be observed [32]. Therefore, adequate estimation of radiation dose should be performed in unselected patient cohorts. Despite a high proportion of overweight or obese patients in our current study, many of the high-pitch spiral scans could be performed at 80 kVp (59/122; 48.4%), and many prospective sequence scans and retrospective spiral scans even used 70 kVp (26/60, 49/96; 43.3%, 51.0%, respectively). The higher percentage of low kV studies is probably the main reason for the significantly higher mean vessel attenuation in the retrospective spiral and prospective sequence group in our study, which is in line with previous studies [17, 31].

Previously, low-dose protocols were limited by high image noise and subsequently inferior image quality. However, the emergence of third-generation iterative reconstruction techniques (ADMIRE, Siemens) helped to maintain diagnostic image quality after reduction of tube current by decreasing image noise compared to filtered back projection [33, 34]. In our study, lower image noise resulted in higher mean signal-to-noise and contrast-to-noise ratios in the high-pitch spiral group compared to the prospective sequence and retrospective spiral group, at similar subjective image quality.

We did not use pulsing in our retrospective spiral scans, as we applied this protocol to patients with high heart rates and arrhythmias. Therefore, we considered it favorable to have the possibility for ECG editing and retrospective selection of the optimal reconstruction interval throughout the cardiac cycle, irrespective of possible ECG misregistration. As a consequence, radiation dose in our retrospective spiral group was relatively high compared to the two other groups. However, we consider the median effective dose of 4.77 mSv a reasonable dose for a heart exam in this challenging patient group. Additionally, retrospective spiral scans allow for functional assessment of the heart, e.g., calculation of left ventricular ejection fraction, which however was not subject of the present study.

We acknowledge that, although the patient population in our study was not highly selected, there are some limitations. First, since the cCTA scans were clinically indicated, there was at least some level of selection involved. Moreover, this was a single-center study and therefore our results may not necessarily be transferable to other sites with different patient collectives. Our results are only valid for the third-generation dual-source CT of a single vendor. Radiation dose and image quality were not compared to previous generation dual-source CTs or scanners from other vendors in the same patients for reasons of repeat radiation and contrast material exposure. Furthermore, patients in this study were not randomized to the different scan protocols but were assigned to the protocol considered most appropriate based on their heart rate. Finally, the high-pitch group featured fewer patients above a BMI of 30 compared to the other two protocols, which might have influenced the analysis.

In conclusion, cCTA with sufficient image quality is achievable at reasonably low radiation exposure in a real-world patient collective with a high overall proportion of overweight or obese patients. The data provided in our study allow for an estimation of radiation dose in cCTA depending on patient habitus and scan protocol in daily clinical routine.

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Compliance with ethical standards

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Statistics and biometry No complex statistical methods were necessary for this paper.

Informed consent Written informed consent was obtained from all subjects (patients) in this study.

Ethical approval Institutional Review Board approval was obtained.

Methodology
• Retrospective
• Observational
• Performed at one institution

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