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ORIGINAL PAPER

Image quality in low-dose coronary computed tomography angiography with a new high-definition CT scanner

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Abstract A new generation of high definition computed tomography (HDCT) 64-slice devices complemented by a new iterative image reconstruction algorithm—adaptive statistical iterative reconstruction, offer substantially higher resolution compared to standard definition CT (SDCT) scanners. As high resolution confers higher noise we have compared image quality and radiation dose of coronary computed tomography angiography (CCTA) from HDCT versus SDCT. Consecutive patients ($n = 93$) underwent HDCT, and were compared to 93 patients who had previously undergone CCTA with SDCT matched for heart rate (HR), HR variability and body mass index (BMI). Tube voltage and current were adapted to the patient's BMI, using identical protocols in both groups. The image quality of all CCTA scans was evaluated by two independent readers in all coronary segments using a 4-point scale (1, excellent image quality; 2, blurring of the vessel wall; 3, image with artefacts but evaluative; 4, non-evaluative). Effective radiation dose was calculated from DLP multiplied by a conversion factor (0.014 mSv/mGy $\times$ cm). The mean image quality score from HDCT versus SDCT was comparable (2.02 $\pm$ 0.68 vs. 2.00 $\pm$ 0.76). Mean effective radiation dose did not significantly differ between HDCT (1.7 $\pm$ 0.6 mSv, range 1.0–3.7 mSv) and SDCT (1.9 $\pm$ 0.8 mSv, range 0.8–5.5 mSv; $P =$ n.s.). HDCT scanners allow low-dose 64-slice CCTA scanning with higher resolution than SDCT but maintained image quality and equally low radiation dose. Whether this will translate into higher accuracy of HDCT for CAD detection remains to be evaluated.

Keywords High-definition computed tomography · Coronary angiography · Image quality · Radiation dose

Abbreviations

ASIR	Adaptive statistical iterative reconstruction
CT	Computed tomography
CCTA	Coronary computed tomography angiography
CAD	Coronary artery disease
HDCT	High definition computed tomography
SDCT	Standard definition computed tomography

Introduction

With the introduction of 64-slice computed tomography (CT) in 2004, coronary CT angiography (CCTA) entered the clinical arena [1–3]. With further technical advancements, such as the introduction of dual-source CT [4] or the introduction of radiation dose saving algorithms including prospective ECG-triggering [5], CCTA continuously established itself in daily routine. Nowadays, CCTA can be considered as an important clinical tool to rule-out coronary artery disease (CAD), especially in patients with a low-intermediate pre-test probability [6–8]. Several single-centre studies have documented the prognostic value of

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CCTA for predicting both all-cause mortality and major adverse cardiac events [9–15], which has been recently confirmed in a large multicenter registry (CONFIRM) [16].

Although CCTA is a well established tool for CAD detection, some limitations still apply which may affect image quality and diagnostic accuracy in some patients, mainly related to spatial and temporal resolution especially in patients with high or irregular heart rate (HR) or increased noise in very obese patients.

New high-definition CT (HDCT) scanners have recently been introduced with gemstone detectors offering a substantially improved spatial resolution (0.23 × 0.23 mm in-plane resolution), complemented by a new iterative image reconstruction algorithm—adaptive statistical iterative reconstruction (ASIR)—to compensate for the increased noise due to the higher spatial resolution. However, the direct comparison of image quality from HDCT versus standard definition CT (SDCT) in a clinical setting is lacking.

Therefore, it was the purpose of this study to compare the image quality of low-dose 64-slice CCTA from HDCT versus SDCT.

Methods

Patients

Ninety three consecutive patients (64 males and 29 females; mean age 56 ± 13 years; age range 22–85 years) were referred to the HDCT for the evaluation of suspected or known CAD or preoperative work-up; they were prospectively enrolled in the present study if there was none of the following exclusion criteria: hypersensitivity to iodinated contrast agent, renal insufficiency (creatinine levels >150 mmol/L, or >1.7 mg/dL) or non-sinus rhythm.

These patients were compared with 93 retrospectively enrolled patients (55 males and 38 females; mean age 56 ± 12 years; age range 30–89 years), who had previously undergone SDCT and were automatically matched for heart rate (HR), HR variability (defined as standard deviation of the HR during scanning) and body mass index (BMI). The need for written informed consent was waived by the institutional review board (local ethics committee) due to the nature of the study with sole clinical data collection.

CCTA data acquisition

Prior to the CCTA examination intravenous metoprolol (5–20 mg) (Beloc, AstraZeneca, London, UK) was administered if necessary to achieve a target heart rate <63 bpm. All patients received a single dose of 2.5 mg isosorbiddinitrate sublingual (Isoket, Schwarz Pharma, Monheim, Germany) 2 min prior to the scan (Table 1). For scanning, 40.0–100.0 mL of iodixanol (Visipaque 320, 320 mg/mL, GE Healthcare, Buckinghamshire, UK) at a flow rate of 3.5–8.0 mL/s followed by 50 mL saline solution was injected into an antecubital vein via an 18-gauge catheter; the amount of contrast material and the flow rate were either adapted to the body surface area or body mass index as previously published [17, 18]. Bolus tracking was performed with a region of interest placed into the ascending aorta.

Table 1 Patient demographics

	SDCT	HDCT	*P*
Number of patients	93	93	
Body mass index (kg/m^2)	27 ± 4 (18–41)	27 ± 4 (18–42)	0.98
Heart rate (bpm)	61 ± 6 (46–75)	61 ± 7 (44–77)	0.93
Heart rate variability (bpm)	1.7 ± 1.4 (0.3–11.7)	2.0 ± 2.5 (0.3–20.2)	0.98
Female/male	38/55	29/64	0.19
Age (years)	56 ± 12 (30–89)	56 ± 13 (22–85)	0.74
Administration of			
Beta-blocker	66 (71 %)	44 (47 %)	0.01
Nitrogylcerin	88 (95 %)	87 (94 %)	0.52
Coronary risk factors			
Smokers	32 (34 %)	31 (33 %)	0.92
Hypertension	41 (44 %)	37 (40 %)	0.59
Diabetes	15 (16 %)	9 (10 %)	0.19
Positive family history	34 (37 %)	26 (28 %)	0.17
Dyslipidemia	43 (46 %)	37 (40 %)	0.41
Clinical symptoms			
None	24 (26 %)	19 (20 %)	0.41
Typical angina	21 (23 %)	35 (38 %)	0.03
Atypical chest pain	33 (36 %)	29 (31 %)	0.57
Dyspnoea	8 (9 %)	8 (9 %)	0.98

CCTA protocol

HDCT examinations were performed with a Discovery CT750 HD scanner (GE Healthcare), using high resolution (0.23 mm isotropic resolution) scan and HD reconstruction kernel, SDCT examinations were performed with a LightSpeed VCT XT scanner (GE Healthcare). Except the differences in isotropic resolution, HDCT scan parameters were identical with SDCT.

All scans (HDCT and SDCT) were performed with prospective ECG-triggering (SnapShot Pulse, GE Healthcare) and the following scanning parameters: slice acquisition 64 × 0.625 mm, smallest X-ray window (only 75 % of the RR-cycle), z-coverage 40 mm with an increment of 35 mm, gantry rotation time 350 ms, BMI adapted tube voltage (100 kV: BMI < 25 kg/m^2, 120 kV: BMI ≥ 25 kg/m^2) and effective tube-current (450 mA: BMI < 22.5 kg/m^2, 500 mA: BMI 22.5–25 kg/m^2, 550 mA: BMI 25–27.5 kg/m^2, 600 mA: BMI 27.5–30 kg/m^2, 650 mA: BMI > 30 kg/m^2). Scanning was performed from below the tracheal bifurcation to the diaphragm, choosing 3–5 scan blocks (field of view 11–18 cm). By choosing the smallest possible window at only one distinct enddiastolic phase of the RR-cycle (i.e. 75 %) we ascertained the lowest achievable effective radiation dose exposure.

The effective dose of CCTA was calculated as the product of the dose-length product (DLP) times a conversion coefficient for the chest ($k = 0.014$ mSv/mGy × cm) as suggested by the European Working Group for Guidelines on Quality Criteria in CT [19]. HDCT coronary angiography images were reconstructed using 30 % ASIR (clinical standard in our institution). Images from SDCT were reconstructed using filtered back projection. All images were transferred to an external workstation (AW 4.4, GE Healthcare) for analysis.

CCTA image analysis

The image quality of all 186 CCTA scans was interpreted independently by two experienced readers using axial source images. Coronary arteries were divided into sixteen segments for analysis of CCTA data as suggested by the American Heart Association [20]: the right coronary artery included segments 1–4, the left main artery and the left anterior descending artery included segments 5–10, and the left circumflex artery included segments 11–15. Segment 16 was defined as the intermediate artery, if this artery was present. We included and evaluated all segments with a diameter of at least 1.5 mm at their origin. Image quality was evaluated on a 4-point scale (1, excellent image quality; 2, blurring of the vessel wall; 3, image with artefacts but evaluative; 4, non-evaluative). If differences in image quality scoring between readers were ≤1, the mean was calculated; only if the difference was >1, a consensus reading was performed.

Statistical analysis

Quantitative variables were expressed as mean ± standard deviation and categorical variables as frequencies and percentages.

Cohen's Kappa statistics were calculated for inter-observer agreement of image quality assessment. Mann–Whitney-*U* tests were used to determine differences between HDCT and SDCT with regard to total effective radiation dose, heart rate, heart rate variability, BMI, age, and amount of administered contrast material; χ^2 tests were used to determine differences image quality scores, administration of beta-blockers and nitrogylcerin, gender, coronary risk factors, and clinical symptoms, prevalence of known CAD.

A *P* value of <0.05 was considered to indicate statistical significance, all reported *P* values were two-sided and were not adjusted for multiple testing. SPSS software (IBM, SPSS Statistics, Version 20) was used for statistical testing.

Results

Between August and November 2011, 100 patients were consecutively enrolled to undergo HDCT. Seven patients were not scanned because heart rates >63 bpm despite beta-blocker administration ($n = 5$), atrial fibrillations ($n = 1$) or impaired renal function ($n = 1$). HDCT was successfully performed in the remaining 93 patients (64 males and 29 females; mean age 56 ± 13 years; age range 22–85 years), of whom 31 were smokers (33.3 %), 9 had diabetes (9.7 %), 26 had a positive family history for CAD (28.0 %), 37 had dyslipidemia (39.8 %), and 37 had arterial hypertension (39.8 %). This study group (HDCT) was complemented by retrospectively enrolled patients previously scanned with identical protocol [17, 18] selected in order to the best match of the HDCT group with regard to HR, HR variability and BMI. Demographics of the final two patient populations are given in Table 1.

Image quality

In 186 patients, a total of 2130 coronary artery segments with a diameter ≥1.5 mm were evaluated (of theoretically 2976 possible segments in 186 patients with 16 coronary segments, 846 segments were missing due to anatomical variants or a vessel diameter of less than 1.5 mm at their origin). There was no significant difference in the amount of applied contrast material between both groups (HDCT: 70 ± 15 mL, SDCT: 72 ± 15 mL; P = n.s.). Inter-observer agreement for image quality rating was "fair" (Kappa = 0.31).

In the HDCT group 1002 coronary segments (94.1 %) were of diagnostic image quality (score 1–3), i.e. 142 segments (13.3 %) were rated to have excellent image quality (score 1), 596 (56.0 %) had blurring of the vessel wall (score 2), and 264 (24.8 %) had minor artifacts (score 3). In 63 coronary segments (5.9 %) image quality was nondiagnostic (score 4).

In the SDCT group 967 coronary segments (90.8 %) were of diagnostic image quality, i.e. 178 segments (16.7 %) were rated to have excellent image quality, 563 (52.9 %) had blurring of the vessel wall, and 226 (21.2 %) had minor artifacts; while nondiagnostic image quality was found in 98 coronary segments (9.2 %).

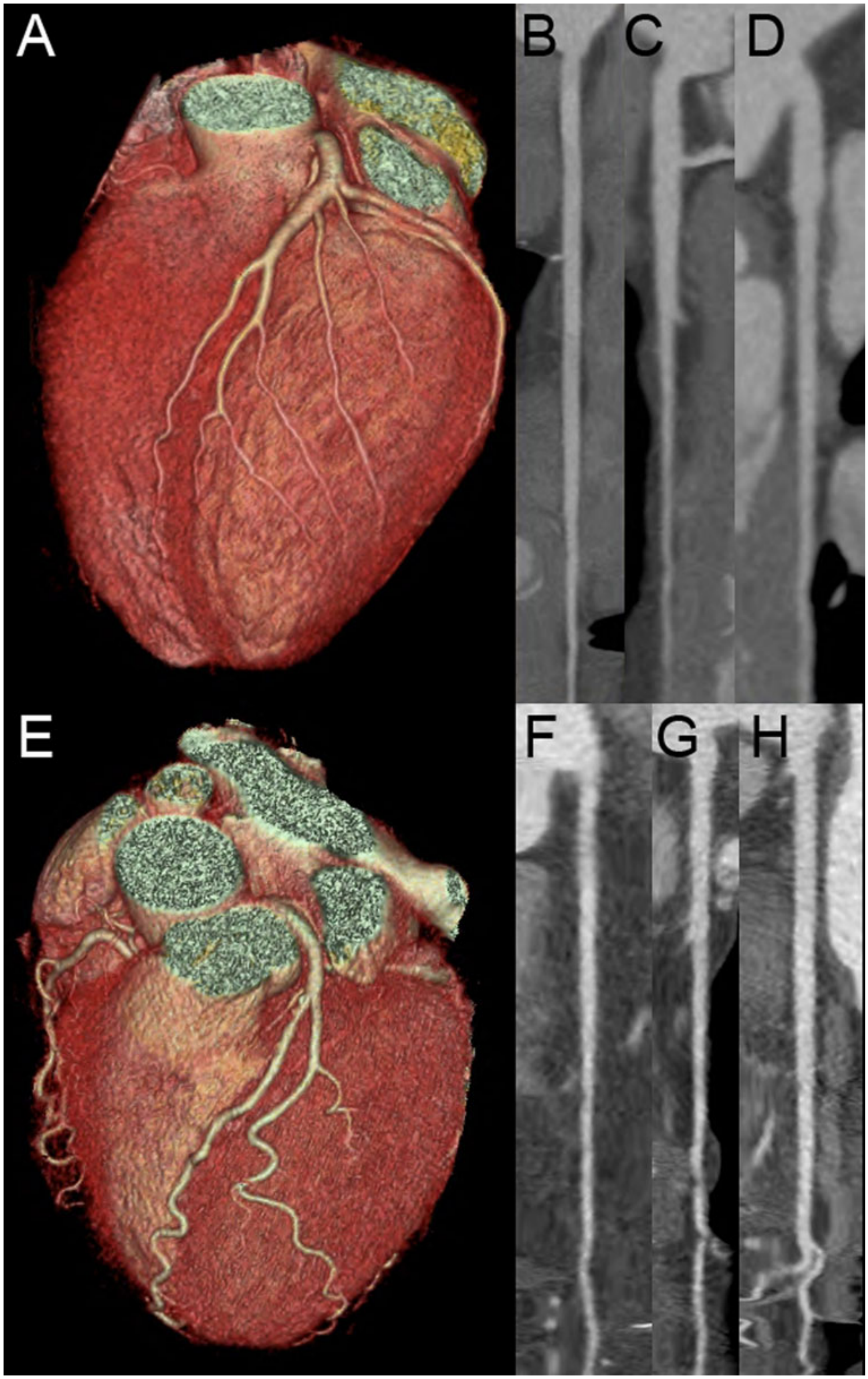

Fig. 1 Two matched patients with comparable image quality (image quality scores 1 or 2 in all coronary segments). *Top line* volume rendered standard-definition CT image of the heart (**a**) and multi planar reconstructions of the right coronary artery (**b**), the left anterior descending artery (**c**) and the circumflex artery (**d**). Heart rate was 58 bpm, heart rate variability of 1.2 bpm and a body mass index 22.0 kg/m^2 (total effective radiation dose 1.4 mSv). *Bottom line* volume rendered high-definition CT image of the heart (**e**) and multi planar reconstructions of the coronary arteries (**f–h**) at a heart rate of 58 bpm, a heart rate variability of 1.1 bpm. Body mass index was 21.9 kg/m^2 (total effective radiation dose 1.1 mSv)

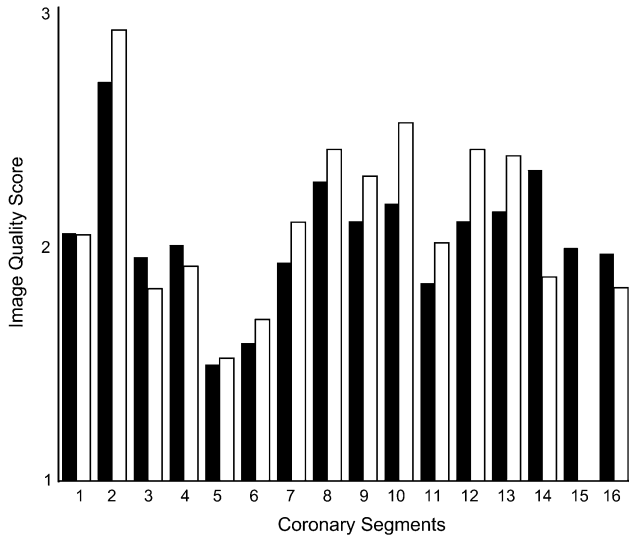

Fig. 2 Mean image quality scores of high-definition CT (*black bars*) and standard-definition CT/*white bars*) in all 16 coronary segments. Notably, for both scanners the worst image quality was detected in segment 2 (mid *right* coronary artery), while the best image quality was noted in segment 5 (*left* main stem). The evaluation of the segment 15 in the SDCT group was not feasible because no vessels with a diameter ≥1.5 mm were detected among the 93 patients

In both groups the overall mean image score was comparable (2.02 in HDCT and 2.00 in SDCT) (Fig. 1) and the lowest image quality was detected in the mid segment of the RCA (segment 2), while the best image quality was found in the left main artery (segment 5) (Fig. 2).

Radiation dose

The mean DLP from the HDCT was 120.9 ± 46.4 mGy × cm (range 72.0–267.0 mGy × cm) resulting in an estimated mean effective radiation dose of 1.7 ± 0.6 mSv (range 1.0–3.7 mSv) compared to the SDCT group with a mean DLP of 136.4 ± 53.7 mGy × cm (range 57.8–393.6 mGy × cm) resulting in an estimated mean effective radiation dose of 1.9 ± 0.8 mSv (range 0.8–5.5 mSv). There was no significant difference between HDCT and SDCT ($P =$ n.s.).

Discussion

The present study is the first to validate image quality and radiation dose in CCTA performed on a 64-slice, so-called high-definition CT scanner, equipped with a new generation gemstone detector, offering an in-plane resolution of 0.23 × 0.23 mm [21].

By nature of physics an improved spatial resolution is paralleled by an increase in image noise if all other parameters are kept equal. To compensate for the image quality degradation an increase in tube-current and/or voltage could be chosen, but this would increase the image dose delivered to the patients. Therefore, new reconstruction algorithms have been developed as an alternative to compensate for the increased image noise without increasing radiation dose. The present study is the first to report successful use of ASIR to compensate for increased image noise as a consequence of increased spatial resolution of HDCT. In fact, our results indicate preserved image quality when comparing HDCT with ASIR to SDCT, although HDCT allows better depiction of small structures including calcifications, small vessels and stents (as evidenced in Fig. 3).

We found no significant difference in mean image quality comparing 64-slice HDCT to SDCT. Heart rate, heart rate variability and BMI have been previously established as main extrinsic—i.e. patients-related rather than scanner-related—determinants of image quality in low dose 64-slice CCTA scanning [18, 22]. High heart rates and high heart rate variability will usually lead to motion or stair-step artefacts in CCTA, which can either be overcome by lowering the patients heart rate and heart rate variability with beta-blockers or by increasing the temporal resolution of the scanner [4]. With the new HDCT device used in the present study gantry rotation remained unchanged compared to SDCT, resulting in an identical temporal resolution. The latter can be underlined by the fact, that the lowest image quality was found in the mid part of the right coronary artery (RCA) in both study groups; the mid part of the RCA is the coronary segment with the fastest coronary motion velocity [23], and therefore most prone to motion artefacts in CCTA [24].

A high patient's BMI on the other hand impairs image quality due to increased image noise by scattering and absorption of radiation [25, 26]. Since absorption of the radiation beam mainly occurs in the patient's soft tissue and hereby causes beam hardening, images of patients with a greater BMI are produced by harder radiation beams than images of patients with a smaller BMI. In the present study a standardized adjustment of the X-ray technique for each patient's BMI ensured that the resultant image noise ratio was sufficient for the diagnostic purpose [27] and identical in both study populations. However, the new HDCT also offers a new iterative image reconstruction algorithm, called ASIR, which reduces image noise [28]. Min et al. [28] found superior detection of intrastent luminal area and diameter visualization in an ex vivo HDCT study, which might be explained by the improved spatial resolution of HDCT. As such evaluation was not the aim of the present study, the improved spatial resolution of HDCT did not translate into improved image quality according to the currently used criteria, although better distinction of small

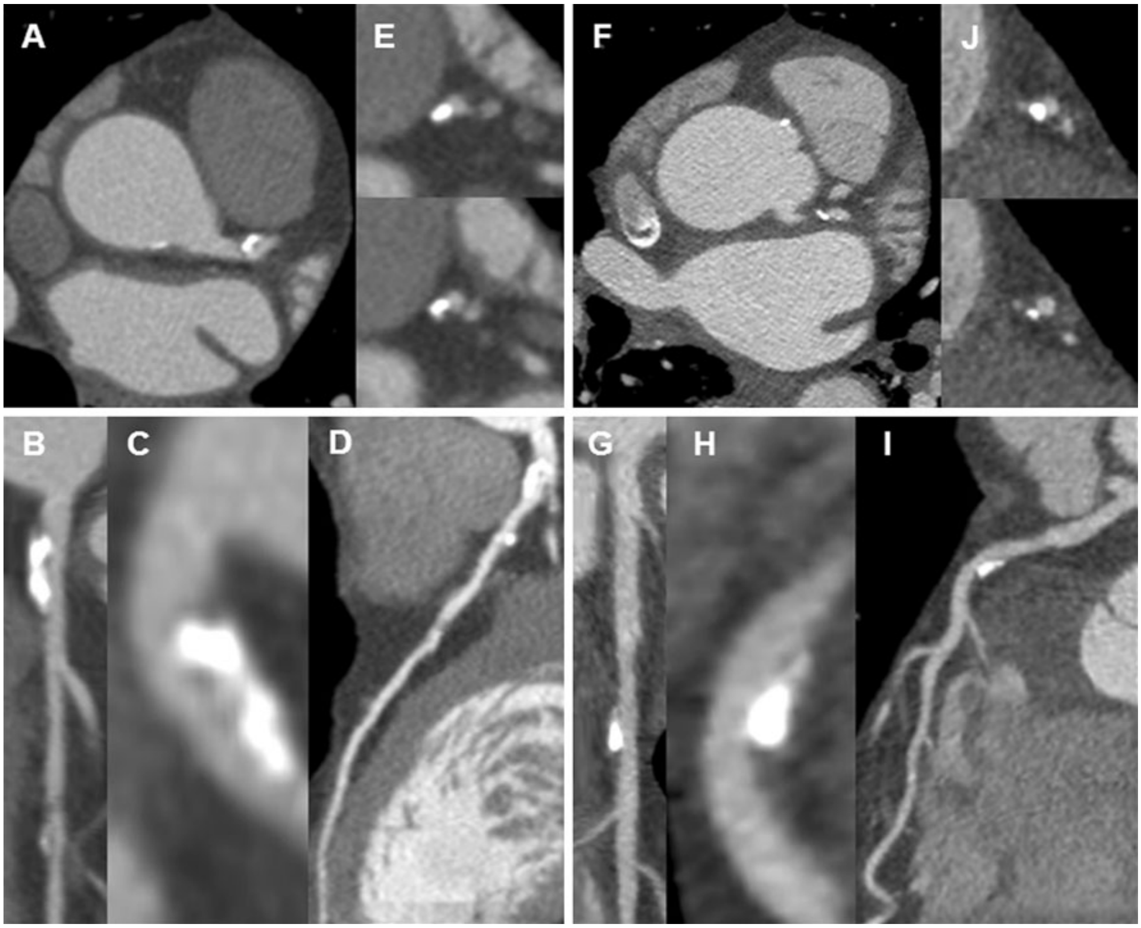

Fig. 3 Two matched patients (SDCT: HR 58 ± 0.7 bpm, BMI 24.0 kg/m^2; HDCT: HR 58 ± 0.9 bpm, BMI 24.0 kg/m^2) with almost identical image quality (1.73 in SDCT and 1.75 in HDCT scan) and effective radiation dose (SDCT: 1.66 mSv; HDCT: 1.51 mSv). Standard-definition CT (**a**–**e**) and high-definition CT (**f**–**j**) images of the heart. Axial images of the heart (**a**, **f**), multi planar reconstructions (**b**, **g**) of the left anterior descending artery (LAD), curved multi planar reconstructions (**c**–**d**, **h**–**i**) of the LAD, cross sectional cuts through the LAD with the calcified plaque (**e**, **j**). These example shows that despite identical image quality evaluation, HDCT might be superior in visualisation of the small details due to the higher resolution of the scanner

structures can be achieved (Fig. 3). Whether the improved spatial resolution will translate into higher accuracy of HDCT CCTA remains to be elucidated. Notably, we validated the image quality of low-dose HDCT, as performed in our daily clinical routine, using 30 % ASIR in all patients. However, we did not systematically analyse the impact of a variable ASIR contributions between 0 and 100 %, which may represent a limitation of the present study.

Furthermore, the use of ASIR might allow a reduction of the total effective radiation dose. In the present study the radiation dose was intentionally kept on an almost equal low level, to guarantee better comparability. Similar image quality scores in both study groups, scanned with the same tube voltage and current, suggest, that a further decrease in radiation dose might be compensated by an increased use of ASIR. This, however, requires further evaluation in future studies.

Conclusion

HDCT scanners allow low-dose 64-slice CCTA scanning with higher resolution than SDCT but maintained image quality and equally low radiation dose. Wether this will translate into higher accuracy of HDCT for CAD detection remains to be evaluated.

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Conflict of interest None.

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