Coronary computed tomography angiography with a consistent dose below 1 mSv using prospectively electrocardiogram-triggered high-pitch spiral acquisition

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Aims	We evaluated the feasibility and image quality of a new scan mode for coronary computed tomography angiography (CTA) with an effective dose of less than 1 mSv.
Methods and results	In 50 consecutive patients (body weight ≤ 100 kg, sinus rhythm ≤60 b.p.m. after pre-medication, coronary CTA was performed using a dual-source CT system with $2 \times 128 \times 0.6$ mm collimation, 0.28 s rotation time, a pitch of 3.2 or 3.4, 100 kV tube voltage and current of 320 mA s. Data acquisition was prospectively triggered at 60% of the R–R interval and completed within one cardiac cycle. Image quality was evaluated using a four-point scale (1 = absence of any artefacts to 4 = uninterpretable). In all 50 patients, imaging was successful. Mean duration of data acquisition was 258 ± 20 ms. Mean dose-length product was 62 ± 5 mGy cm, the effective dose was 0.87 ± 0.07 mSv (0.78–0.99 mSv). Of the 742 coronary artery segments, 94% had an image quality score of 1, 5.0% a score of 2, 0.9% a score of 3, and 4 segments (0.5%) were 'uninterpretable'.
Conclusion	In non-obese patients with a low and stable heart rate, prospectively ECG-triggered high-pitch spiral coronary CTA provides excellent image quality at a consistent dose below 1.0 mSv.
Keywords	Computed tomography • Coronary CT angiography • Dual-source CT • Radiation exposure

Introduction

Coronary computed tomography angiography (CTA) provides increasingly stable image quality and, due to its ability to detect coronary artery stenoses with a high negative predictive value, is considered 'appropriate' for a number of clinical applications.[1] The method's major advantage lies in the fact that, adequate image quality provided, coronary artery stenoses can be ruled out with a high negative predictive value. Coronary CTA can be used to avoid invasive angiography in patients who are symptomatic, but at not at high pre-test likelihood for actually having haemodynamically significant lesions.[1] Such patients are often young, and female patients are often among those who present with atypical symptoms,[2] so that the radiation exposure associated with coronary CTA is of particular concern.[3] Spiral (also termed 'helical') acquisition of data with retrospective ECG gating is most commonly used for coronary CTA.[4] In spiral acquisition, pitch values (table feed per gantry rotation divided by collimated beam width) are typically less than one: Therefore, there is substantial oversampling, meaning that the same level is irradiated during several consecutive rotations of the X-ray gantry. Consequently, radiation exposure is high and effective radiation doses as high as 30 mSv have been reported.[5] However, several techniques have been introduced to lower the radiation exposure of

coronary CTA. ECG-based tube current modulation avoids unnecessary radiation exposure during parts of the cardiac cycle not used for image reconstruction and the use of lower tube voltage further reduces radiation exposure.[6–10] In a recent survey, it was shown that these techniques are frequently applied and the average radiation exposure associated with coronary CTA was 12 mSv.[5] Beyond these measures to reduce radiation doses of retrospectively ECG-gated spiral acquisition, faster gantry rotation times and wider detector arrays with 64 or more simultaneously acquired slices allow 'prospectively ECG-triggered axial acquisition' (also referred to as 'step and shot acquisition'). Owing to the lack of slice overlap, radiation exposure can be reduced substantially, and in some series average doses as low as 2.1 mSv have been reported.[11–19]

Dual-source CT was introduced in 2005 and provides particularly high temporal resolution for coronary CTA. The system uses two X-ray tubes and two detectors arranged at an angle of 90°. Therefore, only one-quarter rotation of the gantry is necessary to acquire the X-ray data for one cross-sectional image. This effectively doubles the temporal resolution when compared with a single- source CT at the same rotation speed.[20–22] In early reports, the ability to perform ECG-triggered spiral data acquisition using very high pitch values (3.0 or more) has been described for dual-source CT.[23,24] The high pitch and fast table speed allow to perform image acquisition for the entire volumetric data set of the heart within a single cardiac cycle. Radiation exposure is low since no slice overlap is used. In fact, appropriate image acquisition parameters may allow a dose below 1 mSv for coronary CTA. Using a recently introduced new generation of dual-source CT that provides an increased number of detectors and faster gantry rotation speed when compared with previous systems, we evaluated the feasibility and image quality of a sub-mSv coronary CTA protocol using prospectively ECG-triggered high-pitch spiral acquisition.

Methods

Patients

Sixty-nine patients were screened for participation. All patients were symptomatic, but at low to intermediate likelihood of coronary artery stenoses based on clinical assessment, with no previously known coronary artery disease, previous coronary artery stent implantation, or coronary artery bypass grafts and had been referred for coronary CTA to rule out haemodynamically relevant coronary artery lesions. Patients with renal failure, known allergy to contrast agent, or atrial fibrillation were not considered for coronary CTA. The only two further inclusion criteria were a heart rate $\leq$60 b.p.m. after pre-medication with beta-blockade and a body weight <100 kg. Both criteria were chosen to optimize image quality since previous experience in coronary CTA suggests better image quality for low heart rates, especially if relatively long data acquisition windows are used[25,26] and because body weight has been shown to influence image noise in low-dose scan protocols.[7] Of the 69 patients screened for participation, 10 had a persisting heart rate >60 b.p.m. after medication with 100 mg atenolol p.o. plus 30 mg metoprolol i.v. (mean heart rate: 70 b.p.m.) and were thus excluded. Nine further patients had a body weight of more than 100 kg (mean: 109 kg) and were also excluded. Thus, 50 consecutive patients were scanned using the prospectively ECG-gated high-pitch spiral protocol. Informed consent was obtained from all patients.

Dual-source computed tomography

All patients with a presenting heart rate >60 b.p.m. received 100 mg atenolol p.o. and were reassessed after 60 min. If heart rate in inspiration remained >60 b.p.m., up to 30 mg metoprolol was injected intravenously, using repeated 5 mg doses. Furthermore, all patients received 0.8 mg nitroglycerine sublingually prior to coronary CTA.

Imaging was performed with a dual-source CT system ('Definition Flash', Siemens Healthcare, Forchheim, Germany) using two X-ray tubes and two detectors arranged at an angular offset of 95°. Each detector enables data acquisition with 64 detector rows of 0.6 mm width (z-axis coverage: 38.4 mm). Together with a z-flying focal spot, this allows simultaneous acquisition of data in 2×128 slices.[20,22] With a gantry rotation time of the system of 0.28 s, half-scan reconstruction provides a temporal resolution of 75 ms in the centre of the field of view. Coronary CTA data sets were acquired using prospectively ECG-triggered high-pitch spiral acquisition ('Flash Spiral'), which is a new type of spiral acquisition developed specifically for dual-source CT. The pitch can be increased substantially, while still allowing image reconstruction due to dual-source geometry. Overlapping radiation exposure is avoided, thus substantially reducing the radiation dose to the patient.

All CT imaging data were acquired in deep inspiration. Coronary CTA was performed with intravenous contrast enhancement. To synchronize acquisition of the coronary CTA data set to arterial enhancement, a 'test bolus' protocol was used; 10 ml contrast agent (Ultravist 370, Bayer Schering Pharma, Berlin, Germany) was followed by 60 ml saline solution, both at flow rates of 6 mL/s, and the time to peak enhancement in the aorta was measured using a series of trans-axial scans acquired in 2 s increments, with the first image being acquired 15 s after the start of injection. For coronary CTA, 60 ml of contrast agent were injected, followed by a 60 ml flush (consisting of 80% saline and 20% contrast), both at flow rates of 6 mL/s. Image acquisition was started with a delay corresponding to the measured contrast transit time plus 5 s. Tube voltage was 100 kV and tube current was 320 mA s/rot. Pitch was 3.2 in the first 28 patients (table feed: 43 cm/s) and 3.4 in the last 22 patients (table feed: 46 cm/s). Image acquisition was prospectively triggered by the patient's ECG and started at 60% of the R-peak to R-peak interval. The total duration of data acquisition was dependent on the selected pitch value and the length of the scan volume, it varied between 220 and 290 ms (median: 270 ms). For image reconstruction, a half-scan reconstruction algorithm was used which provided a temporal resolution of 75 ms in the centre of gantry rotation. While the data window of the topmost cross-sectional image started at 60% of the R-peak to R-peak interval, subsequent images were reconstructed progressively later in the 220–290 ms data acquisition window (Figure 1).[23] Reconstructed slice thickness was 0.6 mm, slice increment was 0.3 mm, and a medium sharp reconstruction kernel was used (B26 f).

For analysis, image data sets were transferred to an off-line workstation (Multimodality Workplace, Siemens Healthcare). Image quality was independently evaluated by two observers blinded to all clinical data. A four-point scale was used (1 = absence of any artefacts; 2 = slight artefacts, but fully evaluable; 3 = artefacts, but evaluable concerning the presence of stenoses; 4 = unevaluable). Image quality was evaluated on a per-segment basis, using the 18-segment model of the Society of Cardiovascular Computed Tomography.[27] In the case of disagreement between the observers, consensus was reached in a joint reading to determine the final image quality score

Figure 1 Image reconstruction in prospectively ECG-triggered high-pitch spiral coronary CT angiography using dual-source CT. The entire period of data acquisition is approximately 260 ms long and is placed in diastole. Images are reconstructed using a half-scan reconstruction algorithm. The temporal resolution of each cross-sectional image is 75 ms. While the first (most cranial) image is reconstructed at the beginning of the 260 ms data window, subsequent images are reconstructed slightly later in the cardiac cycle.

per segment. A per-patient image quality score was defined as the worst score found in any segment for each patient.

Radiation dose was determined based on the dose-length product (DLP) documented in the CT scan protocol, separately for the 'test bolus' acquisition and the coronary CTA acquisition. Effective dose was estimated based on the DLP, using a conversion factor of 0.014 for chest CT in adults.[28]

Statistical analysis

Statistical calculations were performed using PASW Statistics 17.0 (SPSS Inc., Chicago, IL, USA). Unless otherwise indicated, all values are mean values and standard deviations. The Mann−Whitney U test was used to analyse differences between patient groups. The per-patient image quality score was used to compare image quality between different patient groups. $P < 0.05$ was considered to represent a statistically significant difference. Cohen's kappa was calculated to assess interobserver agreement for image quality.

Results

Of the included patients, 12 were female and 38 were male. The average pre-test likelihood of coronary artery stenoses in the 50 included patients, based on age, gender, and symptoms, was $26 \pm 18\%$.[29] The mean body weight was 77 ± 11 kg (range: 42−99 kg) and the mean height was 174 ± 9 cm (range: 150−190 cm). Mean presenting heart rate prior to coronary CTA was 68 ± 9 b.p.m. (range: 45−100 b.p.m.). Six patients did not require any pre-medication because their initial heart rate was <60 b.p.m. Thirty-four patients received one dose of 100 mg atenolol p.o. 45 min before coronary CTA, and 20 patients with a persisting heart rate >60 b.p.m. after oral beta-blockade additionally received metoprolol i.v. at a dose of either 10 mg (eight patients), 20 mg (six patients), or 30 mg (six patients) immediately before CT

data acquisition. After pre-medication, the mean heart rate during coronary CTA was 54 ± 4 b.p.m. (range: 41−59 b.p.m.). No complications occurred as a result of beta-blockade.

Data acquisition was completed in all patients successfully and without complications (*Figures 2* and *3*). The mean length of the scan range was 117 ± 9 mm and the mean duration of data acquisition was 258 ± 20 ms. For 28 patients scanned with a pitch of 3.2, the mean scan range and scan duration was 117 ± 20 mm and 266 ± 22 ms, whereas for 22 patients scanned with a pitch of 3.4, mean scan range and scan duration were 117 ± 9 mm and 253 ± 17 ms.

The mean DLP for the 'test bolus' acquisition was 9.5 ± 1.4 mGy cm, with an estimated effective dose of 0.13 mSv. For coronary CTA, the mean DLP was 62 ± 5 mGy cm (range: 56−71 mGy cm) for all 50 patients, which corresponds to a mean effective dose of 0.87 ± 0.08 mSv (range: 0.78−0.99 mSv). For 28 patients scanned with a pitch of 3.2, the mean DLP was 67 ± 3 mGy cm. For the 22 patients scanned with a pitch of 3.4, mean DLP was 57 ± 2 mGy cm ($P < 0.001$).

A total of 742 coronary artery segments were present (mean of 15 coronary artery segments per patient). Of those, 694 (94%) had an image quality score of 1 (no artefacts) in the consensus reading, 37 segments (5.0%) a score of 2, 7 segments (0.9%) a score of 3, and 4 segments (0.5%) in three patients were rated as 'unevaluable'. All unevaluable segments were in the distal right coronary artery. Overall, the average image quality score per segment was 1.08 ± 0.4. The average per-patient image quality score (reflecting the worst segment for each patient) was 1.4 ± 0.8. It was not significantly different between patients scanned with a pitch of 3.2 and a pitch of 3.4 (1.5 ± 0.9 vs. 1.4 ± 0.8). A score of 1 (no detectable artifacts in any segment) was found in 35 patients. Close interobserver agreement was found for image quality scores. Mean image quality per segment was 1.08 ± 0.4 for reader 1 and 1.09 ± 0.4 for reader 2. Identical scores were given in 720 of 742 segments (97%). Cohen's kappa was 0.77, indicating 'substantial agreement'.[30]

The duration of the image acquisition window did not significantly influence image quality scores. The average per-patient image quality score (worst per-segment score for each patient) was 1.3 ± 0.5 for 22 patients with an acquisition window of less than 270 ms and 1.6 ± 0.9 for 28 patients with an acquisition window of 270 ms or more. However, all three patients in whom at least one segment was rated as unevaluable had a duration of the image acquisition window of 270 ms or more.

Coronary CTA showed the presence of a significant (>50%) luminal stenosis in eight patients (one segment per patient). The affected segment was the proximal left anterior descending coronary artery in three cases, left circumflex coronary artery in three cases, and a large diagonal branch in two cases. All of these patients were referred to invasive coronary angiography. In seven patients, the finding was confirmed by invasive coronary angiography (*Figure 4*), one diagonal branch stenosis was false-positive in CT.

Discussion

Radiation dose is of concern in coronary CTA, but efforts to limit dose must not compromise image quality and the rate of diagnostic
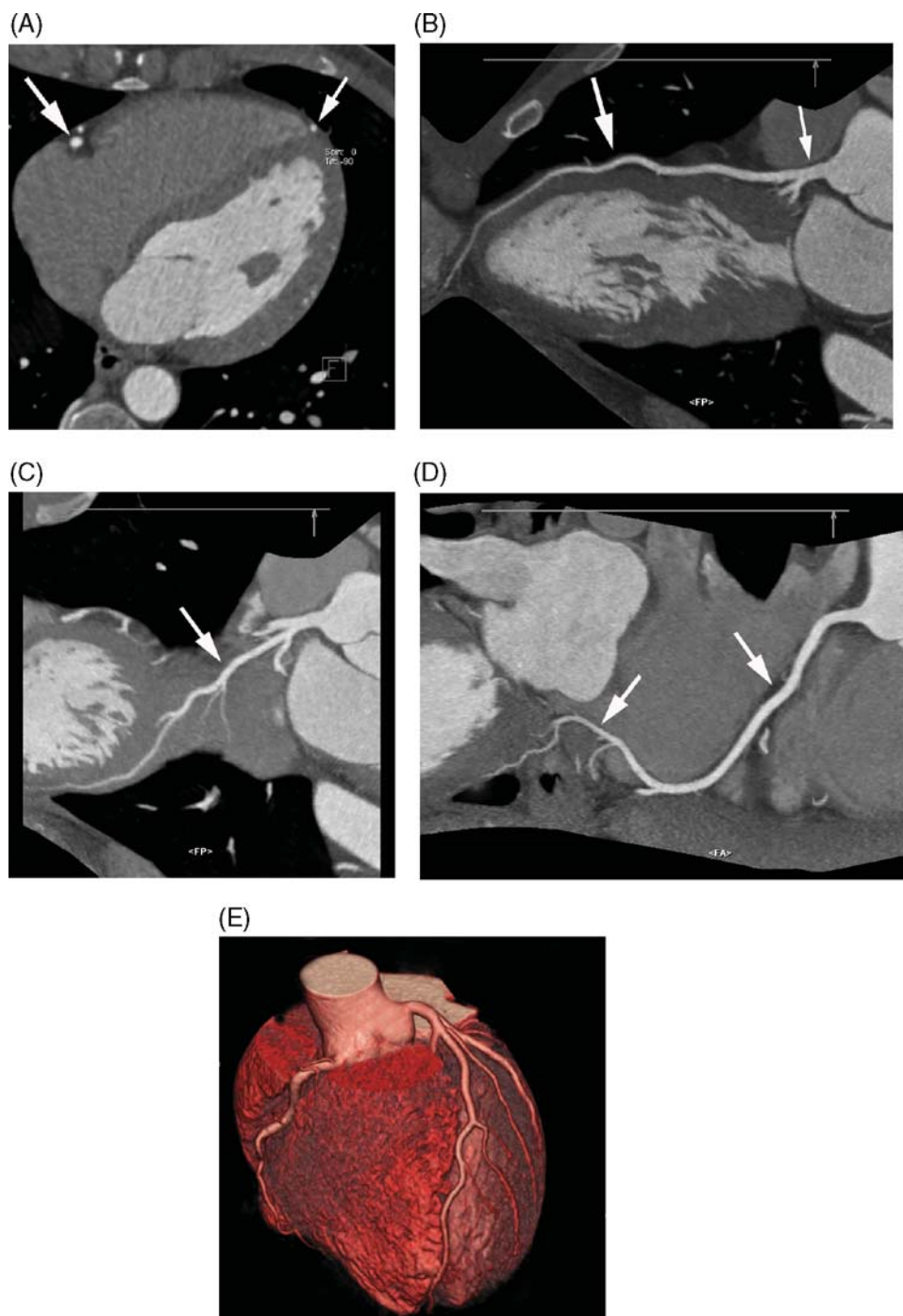
Figure 2 Coronary CT angiography images obtained by prospectively ECG-triggered high-pitch coronary CT angiography. The patient (male, 43 years old, 170 cm, 76 kg) had a heart rate of 56 b.p.m. and was scanned with a pitch of 3.4. DLP for coronary CT angiography was 62 mGy cm (estimated effective dose 0.87 mSv): No coronary artery stenoses are present. (*A*) Transaxial image (0,6 mm slice thickness) at the level of the mid-right coronary artery (large arrow). The small arrow points at the left anterior descending coronary artery. (*B*) Curved multiplanar reconstruction of the left main (small arrow) and left anterior descending coronary artery (large arrow). (*C*) Curved multiplanar reconstruction of the left main and left circumflex coronary artery (arrow). (*D*) Curved multiplanar reconstruction of the right coronary artery (arrows). (*E*) Three-dimensional, surface weighted reconstruction of the heart and coronary arteries.

scans. We used a new prospectively ECG-trigged scan protocol (Flash Spiral), which uses a very high pitch value (up to 3.4). The high pitch value allows coverage of the volume of the heart in a very short time (approximately 260 ms), so that data acquisition can be completed with one single cardiac cycle. From the obtained data, cross-sectional images are reconstructed with a temporal
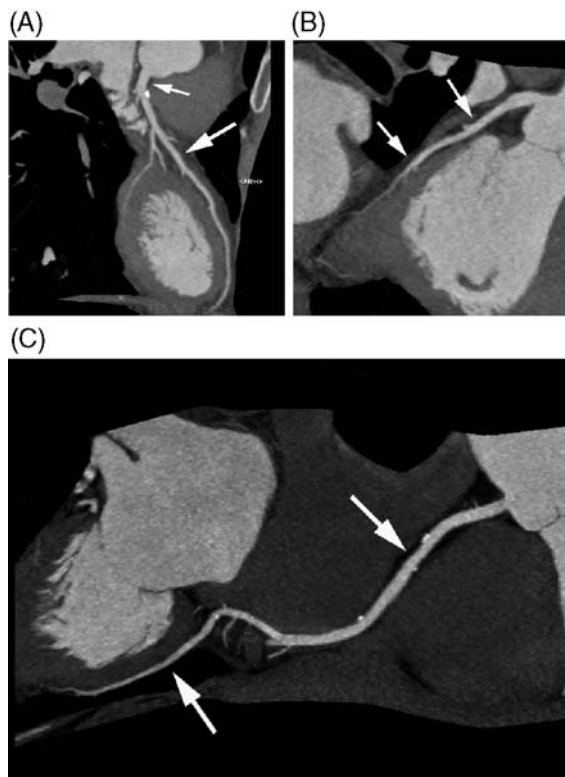
Figure 3 Coronary CT angiography images obtained by prospectively ECG-triggered high-pitch coronary CT angiography in a 48-year-old male patient (183 cm, 78 kg, heart rate 54 b.p.m.). The patient was scanned with a pitch of 3.2. DLP was 64 mGy cm (estimated effective dose 0.89 mSv). The patient has a right dominant coronary pattern. Calcified plaque is present in the left anterior descending and right coronary artery, Stenoses are not present. (*A*) Curved multiplanar reconstruction of the left main (small arrow) and left anterior descending coronary artery (large arrow). A calcified plaque is present in the proximal left anterior descending coronary artery. (*B*) Curved multiplanar reconstruction of the left main and left circumflex coronary artery (arrow), which is very small in the presence of right dominant coronary circulation. (*C*) Curved multiplanar reconstruction of the right coronary artery (arrows). Calcified plaque is present.

resolution of 75 ms. Consecutive cross-sectional images depict the coronary arteries during slightly different instances in time. The most cranial images are obtained at the very beginning of the data acquisition window, and subsequent images (moving in a caudal direction) display the heart in slightly later instants in the cardiac cycle. However, the data window starts at 60% of the cardiac cycle so that all images are diastolic, and transitions between subsequent images are smooth so that the temporal inhomogeneity of the data set is not noticeable in the reconstructed images. In fact, since the entire data acquisition occurs in one cardiac cycle and is limited to diastole, 'misalignment' or 'stair-step' artefacts were not observed. Prospectively ECG-triggered acquisition and the use of a high pitch reduce radiation

exposure to a theoretical minimum because no overlap in data sampling is applied. Also, since data acquisition is completed in one single sweep, unnecessary radiation exposure as the detector enters and leaves the 180° arc necessary for image reconstruction occurs only at the beginning and end of the data sweep, while in conventional, axial imaging protocols such exposure occurs at every scan level.

In a consecutive series of 50 patients with low heart rates after oral beta-blockade and a body weight below 100 kg, we could demonstrate that prospectively ECG-triggered high-pitch spiral coronary CTA results in high-quality images with a low rate of non-diagnostic segments. Imaging parameters were set to provide an estimated effective radiation dose below 1.0 mSv. In fact, the average effective dose was only 0.87 mSv. Although most of our patients were scanned using a pitch of 3.2, the pitch value was increased to 3.4 in the last 22 patients. With an increased pitch value, the duration of image acquisition was even shorter and radiation exposure was further reduced without compromising image quality.

High-pitch spiral acquisition is only possible with dual-source geometry because the fast table motion causes gaps in the trajectory of the first detector which need to be filled in by the second. In addition, a high temporal resolution is necessary to provide artefact-free images with half-scan reconstruction and during a relatively long diastolic window of the cardiac cycle. Heart rate must be low to accommodate the long image acquisition window—which may often require beta-blockade—and regular in order to allow accurate triggering of the image acquisition process. Inconstant heart rates would compromise image quality by causing data acquisition in an unfavourable segment of the cardiac cycle.

Although the presented data highlight the ability to consistently perform sub-mSv coronary CTA in selected patients, our analysis has several limitations. Radiation doses were estimated and not measured, and assessment of image quality was subjective. In this initial evaluation of low-dose coronary CTA, we limited eligible patients to those with optimal conditions for imaging, including a body weight <100 kg as well as a low and stable heart rate. We could demonstrate that image quality was not only diagnostic in the vast majority of cases, but that in more than 90% of coronary artery segments, image quality entirely free of detectable artefact was obtained. On the other hand, our data are limited in that no systematic comparison with invasive coronary angiography was performed and that our study did not include a randomized comparison with other scan modes concerning radiation exposure and image quality. We did not analyse the influence of the calcium score on image quality. Neither did we systematically evaluate the limits for using this scan mode, as far as heart rate and body weight are concerned. In future studies, the potential and limitations of prospectively ECG-triggered high-pitch spiral acquisition for coronary CTA will need to be explored further, and comparisons with appropriate reference standards will need to clarify diagnostic accuracy concerning the detection of stenosis and plaque. Especially in the context of imaging young patients—and possibly, at some point, in the context of imaging asymptomatic individuals for risk stratification (an indication not yet backed by clinical data, which could only be justified once reliable efficacy,
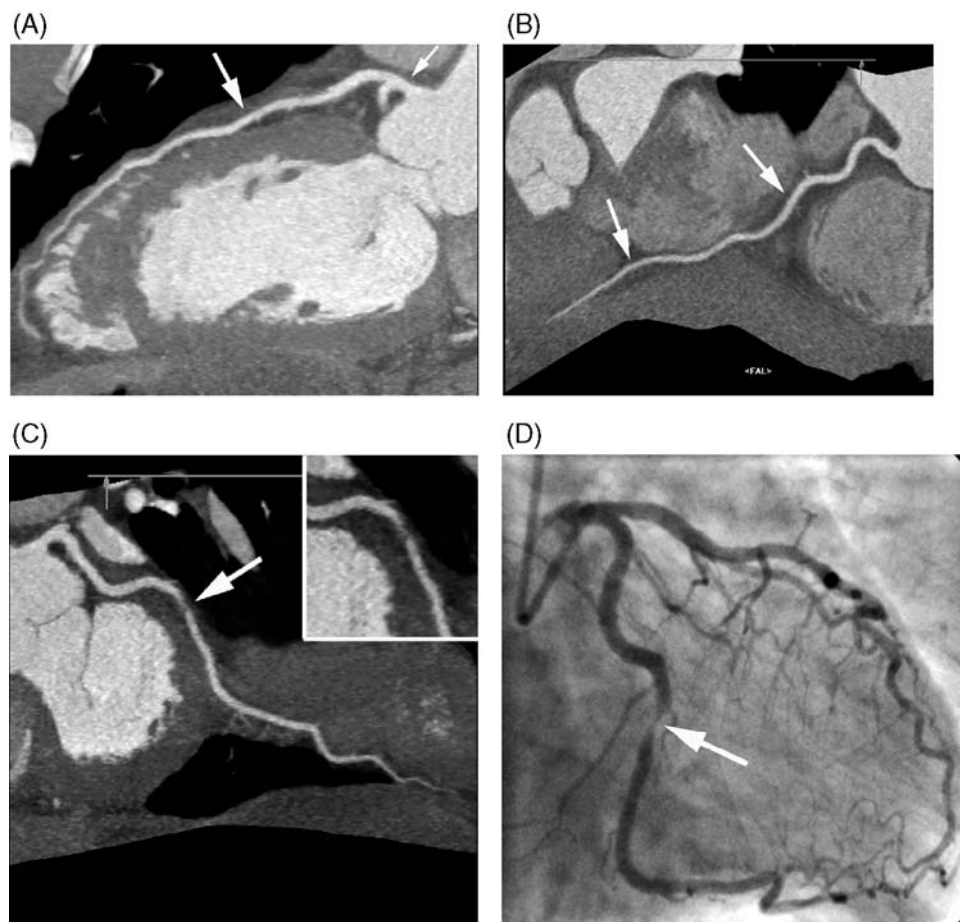
Figure 4 Coronary CT angiography images obtained by prospectively ECG-triggered high-pitch coronary CT angiography in a patient with suspected coronary artery disease (male: 63 years old, 172 cm, 81 kg, heart rate 57 b.p.m.). Pitch was 3.2, DLP was 60 mGy cm (estimated effective dose 0.84 mSv). A high-grade stenosis was found in the proximal left circumflex coronary artery and confirmed by invasive coronary angiography. (A) Curved multiplanar reconstruction of the left main (small arrow) and left anterior descending coronary artery (large arrow). A calcified plaque is present in the proximal left anterior descending coronary artery. (B) Curved multiplanar reconstruction of the right coronary artery (arrows). (C) Curved multiplanar reconstruction of the left main and left circumflex coronary artery (arrow), which displays a high-grade stenosis in the proximal segment (arrow and insert). (D) Corresponding invasive coronary angiogram which conforms a high-grade stenosis (arrow).

cost/effectiveness and risk/benefit data have become available)—this new scan mode is extremely attractive because of the very low associated dose and high image quality.

Funding

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