The International Journal of Cardiovascular Imaging (2019) 35:2239–2248
https://doi.org/10.1007/s10554-019-01678-7

ORIGINAL PAPER

Diagnosis of coronary artery disease in patients with atrial fibrillation using low tube voltage coronary CT angiography with isotonic low-concentration contrast agent

Yuning Pan[1] · Qiuli Huang[1] · Yingchao Zhu[2] · Xinrong Zou[3] · Huimin Chu[4] · Xianfeng Du[4] · Aijing Li[5] · Shizhong Bu[2]

Received: 3 February 2019 / Accepted: 24 July 2019 / Published online: 30 July 2019

Abstract
This prospective study evaluated the image quality and accuracy of coronary computed tomography angiography (CCTA) for diagnosing coronary artery disease (CAD) in patients with atrial fibrillation (AF), in which CCTA used adaptive iterative dose reduction (AIDR) with a low tube voltage and low concentration of isotonic contrast agent. Sixty-eight consecutive patients with AF and suspected CAD were equally and randomly apportioned to two groups and underwent CCTA. In the experimental group, the contrast agent was iodixanol (270 mg I/mL), patients were scanned with 100 kV, and reconstruction was by AIDR. In the conventional scanning (control) group, the contrast agent was iopromide (370 mg I/mL), patients were scanned with 120 kV, and reconstruction was by filtered back projection. The image quality, effective radiation dose (*E*), and total iodine intake of the groups were compared. Thirty-nine patients with coronary artery stenosis later were given invasive coronary angiography (ICA). The groups were similar with regard to mean CT value, noise, and signal-to-noise and contrast-to-noise ratios. The figure of merit of the experimental group was significantly higher than that of the control group, while the *E* and total iodine were significantly lower. Using ICA as the diagnostic reference, the groups shared similar sensitivity, specificity, and false positive and false negative rates for diagnosing coronary artery stenosis. For determining CAD in patients with AF, CCTA with isotonic low-concentration contrast agent and low-voltage scanning is a feasible alternative that improves accuracy and reduces radiation dose and iodine intake.

Keywords Atrial fibrillation (AF) · Computed tomography (CT) · Radiation dose · Contrast medium · Invasive coronary angiography

Introduction

Coronary computed tomography angiography (CCTA) is an effective non-invasive technology to evaluate coronary artery disease (CAD) [1], but arrhythmia will affect the demonstration and evaluation of coronary arteries [2]. In

Yuning Pan and Qiuli Huang contributed equally to this work.

✉ Aijing Li
zheylaj@sina.com

✉ Shizhong Bu
bushizhong@nbu.edu.cn

1 Department of Radiology, Ningbo First Hospital, Ningbo 305010, Zhejiang Province, People's Republic of China

2 Diabetes Research Center, School of Medicine, Ningbo University, 818 Fenghua Road, Jiangbei District, Ningbo 315211, Zhejiang Province, People's Republic of China

3 Department of Endocrinology, Li Huili Easton Hospital of Ningbo Medical Center, Ningbo 305040, Zhejiang Province, People's Republic of China

4 Department of Cardiology, Ningbo First Hospital, Ningbo 305010, Zhejiang Province, People's Republic of China

5 Department of Radiology, Ningbo No. 2 Hospital, 41 Xibei Road, Haishu District, Ningbo 305010, Zhejiang Province, People's Republic of China

particular, patients with atrial fibrillation (AF) often have rapid heart rates (HRs) and irregular ventricular rhythm, which can cause blurring artifacts on CCTA. Therefore, CCTA was once considered contraindicated in patients with AF [1, 2].

The incidence of CAD in patients with AF is very high (about 80%), and the mortality rate is twice that of patients without AF [3]. Therefore, pre-operative pulmonary artery imaging and screening for CAD using multi-slice computed tomography (CT) is important for patients with AF [4]. In recent years, the application of CCTA in AF has become increasingly widespread [5–10]. CCTA using 320-row CT can reduce the radiation dose while maintaining high diagnostic accuracy, and has superior advantages and diagnostic performance for cardiac imaging in patients with arrhythmia, especially AF [5, 8, 11–13].

In patients with AF, multiple cardiac cycle acquisitions increases the radiation dosage by many fold, and a higher volume of contrast agent is needed to maintain vascular enhancement [12, 14–16]. However, according to the principle of as-low-as-reasonably-achievable that has been adopted in recent years, the CT radiation dose for diagnosis should be reduced as much as possible [17]. So too, reducing the amount of iodine in the contrast agent can lower the risk of contrast-induced nephropathy.

Compared with the traditional filtered back projection method of reconstruction, iterative reconstruction can reduce the image noise of CCTA, improve image quality, and reduce radiation dose [18, 19]. Furthermore, low tube voltage technology improves CT attenuation compared with conventional 120 kV scanning, increasing the image value of the enhanced vessel, and supports a rationale for application of low concentration contrast agents [20].

Recently, research in CCTA has focused on combining low-concentration contrast media and low-tube voltage technology [21–23], but results specific to AF patients have not been reported. The present study evaluated the feasibility of CCTA examinations in AF patients for detecting coronary artery stenosis, in which isotonic low-concentration contrast media, third-generation adaptive iterative dose reduction (3D-AIDR) reconstruction, and low-tube voltage is used, relative to traditional scanning.

Materials and methods

This prospective study was approved by the ethics committee of Ningbo First Hospital. All patients provided informed consent.

Patients

Sixty-eight consecutive patients (47 male, 21 female, aged 39–88 years, with a median age of 66 ± 12 years) with persistent AF, and suspected of CAD, were enrolled from June 2016 to August 2017 (Table 1). Patients with any of the following were excluded from this study: pregnant, allergy to iodine contrast agent, severe renal insufficiency (creatinine clearance rate ≤ 120 μmol/L), cardiac insufficiency, unable to hold breath during CCTA, or history of coronary artery bypass transplantation.

The patients were randomly apportioned to either the experimental or control group, with 34 patients in each. In the experimental and control groups, the contrast agent was, respectively, iodixanol (Visipaque, 270 mg I/mL, GE Electric Pharmaceutical, Shanghai) and iopromide (Ultravist, 370 mg I/mL, Bayer Medical Care, Guangzhou). Patients were scanned with 100 kV (experimental) and 120 kV (control), and for reconstruction the 3D-AIDR algorithm (experimental) and filtered back projection method (control) was applied.

Among the study population of 68 patients, 39 with coronary artery stenosis underwent invasive coronary angiography (ICA) after CCTA within 15 days (18 and 21 in the experimental and control groups, respectively).

CCTA scanning method

All CT scans were performed using a 320-row CT scanner (Aquilion ONE, Toshiba, Japan), with inherent arrhythmia removal software (Version 4.51, Toshiba Medical Systems, Nasu, Japan). The collimator was 320 × 0.5 mm, the rotation time was 0.35 s/circle, and the range covered in the *z*-axis was 16 cm.

The patients were strictly trained to hold their breath before scanning. For patients with HR ≥ 70 bpm and without contraindication, 50 mg metoprolol (Astrazeneca Pharmaceutical, Wuxi, China) was orally taken 1 h before CT. The scanning range was from the tracheal bifurcate level

Table 1 General characteristics of the experimental and control groups

	Experimental	Control	P
Gender, male/female	24/10	17/17	0.083
Age (years)	66.24 ± 10.52	65.97 ± 11.27	0.925
BMI (kg/m^2)	24.27 ± 6.73	23.17 ± 5.19	0.430
HR (bpm)	91.38 ± 26.30	95.85 ± 26.45	0.490
HR difference (bpm)[a]	22.50 ± 9.34	23.44 ± 10.77	0.677

[a]Difference between the maximum and minimum HR during the CT acquisition process

to the diaphragm, which was adjusted to cover the entire heart (from 150×150 to 180×180 mm^2). The tube current (330–550 mA) was adjusted according to body mass index (BMI) and the tube voltage. For patients with AF associated with an enlarged left atrium, the setting of the tube current was adjusted based on the anatomy of the chest and the size of the left atrium.

All patients were scanned while supine and feet-in first, using a prospective cardiac electronically controlled trigger sequence and electrocardiographic (ECG) monitoring. For patients with HR < 65, 65–80, and ≥ 80 bpm, the acquisition slope was, respectively, 65–85%, 30–80%, and 25–55% of the RR interval, and the scanning was acquired by 1, 2, and 3 cardiac cycles. Only for patients with HR > 110 bpm, scanning was acquired by 4 cardiac cycles. All patients were administered sublingual nitroglycerin (0.5 mg, Yimin Pharmaceutical, Beijing) 5 min before CT to expand the coronary artery. All nonionic contrast media were placed in a 37 °C incubator before injection.

The contrast medium of each group was injected with a double-cylinder high-pressure injector (Stellant, Medrad, Indianola, PA, USA) and intravenous 20G indwelling needle, through the right median cubital vein with a velocity of 5 mL/s; 30 mL saline as then injected at the same rate. The contrast medium dose was equal to the patient's weight in kg, multiplied by 1.1 mL/kg.

Applying a contrast medium tracer technique (bolus tracking), a region of interest (ROI, with an area of = 100 mm^2) was chosen at the aortic root level to monitor the CT value. The scanning was automatically triggered 4 s later, when the CT value within the ROI reached 180 HU. During scanning, the equipment could synchronously record the patients' ECG information and calculated the HR difference (i.e., the difference between the maximum and minimum HR during the CT acquisition process).

Image reconstruction and post-processing

The image reconstruction consisted of three steps: automatic peak phase, ECG editing, and multiple phase selection. For the optimal phase automatically reconstructed by the device, when there were artifacts ECG editing was performed; half-scanning reconstruction when HR < 65 bpm, or multi-sector reconstruction otherwise. To rebuild, the phase with the minimum number of artifacts was chosen from planes taken at 10-ms intervals. All images were reconstructed by adopting absolute phases and using the soft tissue convolution function, with a reconstructed thickness of 0.5 mm and interval of 0.25 mm. The reconstructed images were transferred to the post-processing Workstation (VitreaFx 4.0) for further analysis. The image processing included maximum intensity projection, curved planar reconstruction, and volume rendering.

Image quality evaluation

Subjective evaluation

Two experienced radiologists (both with > 5 years' experience in cardiac CT diagnosis) evaluated all coronary segments (diameter > 1.5 mm) on the original cross-sectional images, curved planar reconstruction, and volume rendering images, in accordance with the American Heart Association segment standard for the coronary artery [24]. The radiologists independently analyzed the images based on the double-blind principle. The quality of the images was scored as excellent, good, moderate, or poor, with 4 to 1 points, respectively [25].

Objective evaluation

All measurements were conducted using a fixed window width of 800 HU and window level of 100 HU. Four ROIs were drawn: at the left main coronary artery (LMA), proximal segments of the left anterior descending coronary artery (LAD), left circumflex coronary artery (LCX), and right coronary artery (RCA). As far as possible, the ROIs encompassed the maximum round or oval area, barring the blood vessel walls, and avoiding wall calcification, and plaque. The CT value within the ROI was measured, and its standard deviation was considered the image noise. The CT value of the muscle tissue of the anterior chest wall was measured, with the standard deviation considered background noise; its ROI was drawn to avoid adipose tissue and bone artifacts as much as possible (Fig. 1).

The signal-to-noise ratio (SNR) was calculated as the average CT value of the lumen divided by the standard deviation of the CT value of the lumen. The contrast-to-noise ratio (CNR) was the difference between the mean CT value of the lumen and the average CT value of the muscle tissue of the anterior chest wall, divided by the standard deviation of the CT value of the muscle tissue. The figure of merit (FOM) was defined as the square of the CNR divided by the effective radiation dose (*E*).

Evaluation of radiation dose and total iodine content

The radiation dose of CCTA was counted, not including the positioning image scanning and the trigger scanning. The volumetric CT dose index, and dose length product, of each patient were automatically generated and recorded by the computer, and the effective radiation dose (*E*) was calculated as: $E = \text{dose length product} \times 0.014$ mSv/mGy/cm. The total iodine intake was calculated as the concentration of contrast agent (mg/mL) × the dose of contrast agent (mL) divided by 1000.

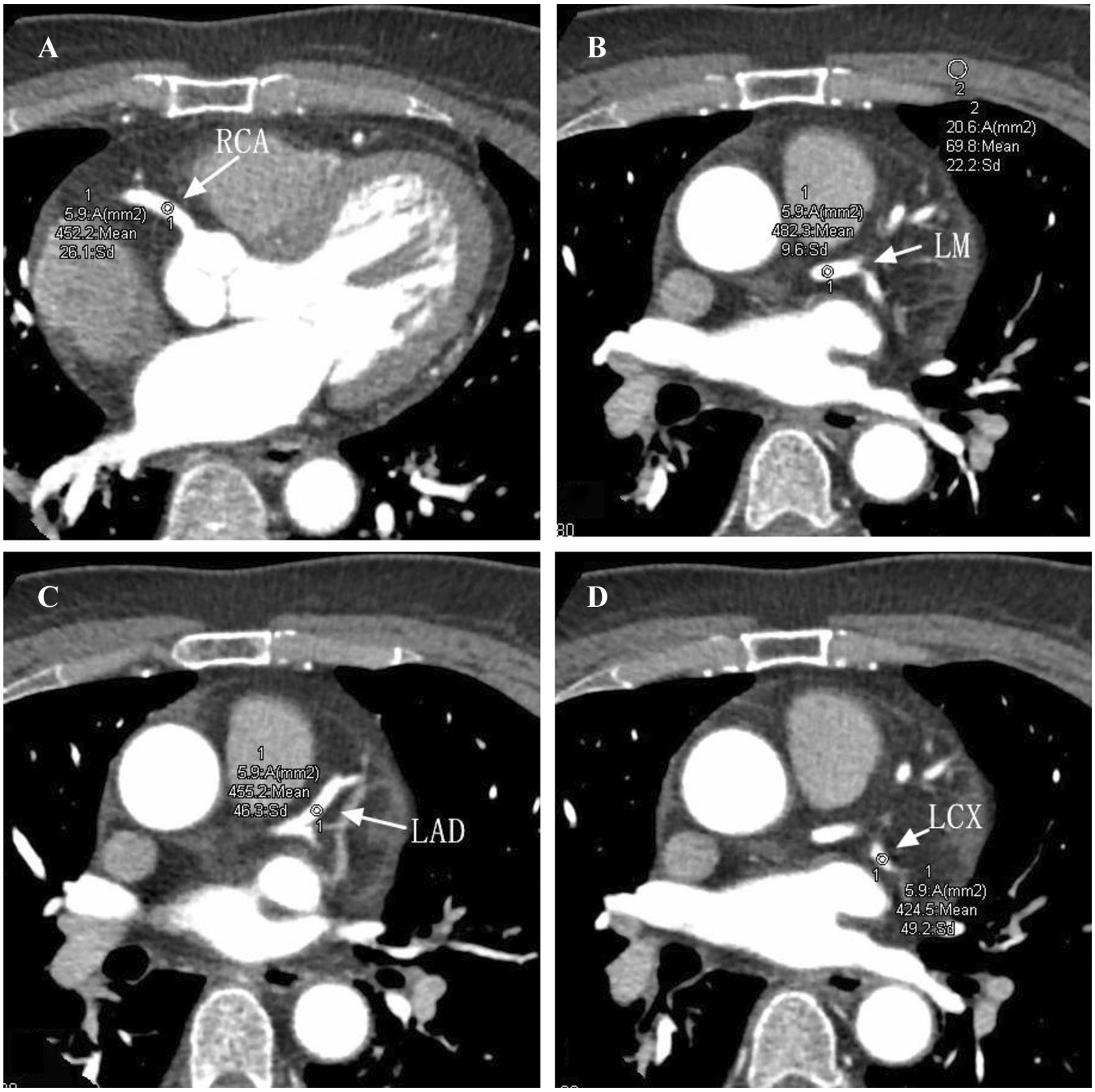

Fig. 1 CT values of each main coronary artery and background noise. **a** RCA, **b** LMA and background noise and **c** LAD, **d** LCX

Comparative analysis of ICA and CCTA

All ICA exams were performed within 15 days after CCTA by a cardiologist, with a C-arm large-plate digital angiography machine (Philips Allura Xper FD-10, Philips Healthcare Nederland). A 6F or 5F coronary angiography catheter was inserted through the right femoral or radial artery, and left and RCA angiography was performed in sequence. Iopromide (370 mg I/mL) was used during the ICA, with a bolus injection of 4–8 mL each time.

All images were evaluated by two experienced cardiovascular radiologists in accordance with the double-blind method. The degree of coronary stenosis was assessed by the visual diameter method. Discordant results were discussed until a consensus was reached. Lumen stenosis of 0% was considered nil visible stenosis. Percentages of 1–24%, 25–49%, 50–69%, and 79–99% were categorized as minimal, mild, moderate, and severe stenosis, respectively. A lumen with 100% stenosis was considered occluded [26, 27]. The accuracy of CCTA for diagnosing CAD was evaluated, adopting the ICA results as the gold standard diagnostic reference.

Statistical analysis

All statistical analyses were performed using SPSS 19.0 software. All measurement data are presented as the mean ± standard deviation. Basic data (i.e., age, BMI, HR, and HR difference), image quality, effective radiation dose E, and total iodine intake of the experimental and control groups were compared using independent sample t-tests. The enumerative data of the groups were compared with the chi-squared test. The sensitivity, specificity, positive predictive value, and negative predictive value of CCTA for diagnosing stenosis of the coronary artery were calculated, using the ICA results as diagnostic reference. The differences for diagnosing stenosis of the coronary artery between ICA and CCTA were compared by chi-squared test, and Fisher's exact test was used for comparisons among groups. The kappa test was applied to evaluate the consistency of the two radiologists. $P < 0.05$ was considered statistically significant.

Results

The experimental and control groups were statistically comparable with regard to age, gender, BMI, HR, and HR difference (Table 1).

Subjective evaluation of image quality

In the 68 patients, 892 coronary artery segments were evaluated by CCTA (128 segments were not evaluated due to anatomical variations or diameter < 1.5 mm). In the experimental and control groups, 94.2% (424/450) and 95.2% (421/442) of the coronary artery segments, respectively, were adequate for diagnosis; the quality scores of the two groups were comparable (3.07 ± 0.82 and 3.18 ± 0.77; Table 2). The two observers were consistent with regard to image quality scores of both groups (*kappa* value = 0.82, P = 0.023).

Objective evaluation of the image quality

Over the entire study population, the average CT value of the measured vessels was > 250 HU. The average CT values of the experimental and control groups were comparable, specifically 373.4 ± 35.1 HU and 387.0 ± 42.51 HU, respectively. The SNR and CNR of the two groups were each also similar. The FOM of the experimental group was significantly higher than that of the control group (Table 3).

Table 2 Subjective assessment of image quality via scoring for coronary arteries of the experimental and control groups

Score	Experimental	Control
1	26 (5.8)	21 (4.8)
2	48 (10.7)	36 (8.1)
3	210 (46.7)	225 (50.9)
4	166 (36.8)	160 (36.2)
Total, n	450	442

Data are reported as *n* (%) segments, unless noted otherwise

Table 3 Objective assessment for coronary arteries of the experimental and control groups

	Experimental	Control	*P*
LM			
CT	385.7 ± 32.1	378.8 ± 41.1	0.307
CNR	13.4 ± 3.9	14.3 ± 3.6	0.320
SNR	11.6 ± 1.8	11.5 ± 1.7	0.839
FOM	37.8 ± 27.5	21.7 ± 12.5	0.000
LAD			
CT	376.2 ± 44.6	391.0 ± 41.9	0.085
CNR	14.0 ± 3.0	13.4 ± 3.3	0.494
SNR	10.0 ± 1.6	9.8 ± 1.3	0.407
FOM	37.3 ± 15.4	18.8 ± 10.5	0.000
LCX			
CT	384.8 ± 29.1	387.4 ± 38.4	0.721
CNR	13.9 ± 3.1	12.9 ± 3.7	0.222
SNR	12.2 ± 2.1	12.0 ± 1.6	0.615
FOM	37.2 ± 17.0	17.6 ± 11.1	< 0.001
RCA			
CT	386.9 ± 34.4	390.6 ± 48.7	0.715
CNR	13.3 ± 3.0	13.2 ± 3.4	0.888
SNR	12.4 ± 2.1	12.2 ± 2.0	0.722
FOM	33.6 ± 12.93	18.0 ± 10.45	< 0.001

Values reported as HU, unless noted otherwise

Evaluation of radiation dose and total iodine intake

In the experimental group, the volumetric CT dose index and effective radiation dose *E* were both significantly lower than that of the control group (Table 4). The *E* value of the experimental group was 51.6% that of the control group. While the total iodine intake of the two groups was statistically similar, the total amount of iodine in the experimental group was significantly lower than that of the control group.

CCTA results relative to ICA

Using the ICA results as the reference, the experimental and control groups were statistically similar with regard to sensitivity, specific, and false positive and false negative rates for

Table 4 Comparison of effective radiation dose *E* and iodine intake between the experimental and control groups

	Experimental	Control	*t*	*P*
$CTDI_{vol}$ (mGy)	28.88 ± 7.78	56.00 ± 18.69	8.793	< 0.001
E (mSv)	4.72 ± 1.19	10.76 ± 3.76	− 8.434	< 0.001
CM (mL)	70.63 ± 15.83	71.61 ± 16.12	0.241	0.811
Total iodine (g)	19.06 ± 4.27	26.50 ± 5.97	4.534	< 0.001

$CTDI_{vol}$ volumetric CT dose index

diagnosing coronary artery stenosis ≥ 50% (Table 5; Figs. 2, 3).

Discussion

This prospective study evaluated the feasibility of CCTA for AF patients suspected of coronary artery stenosis, in which isotonic low-concentration contrast media, AIDR reconstruction, and low-tube voltage is used. Patients underwent CCTA use 320-spiral volume CT with prospective ECG triggered scanning. The results showed that there was no reduction in image quality or diagnostic accuracy for CAD when using CCTA with isosmotic low concentration contrast agent and low tube voltage.

Most CCTA studies for patients with AF have employed retrospective ECG gated spiral scanning. In these studies, the radiation dose and iodine intake of patients was high,

Table 5 CCTA diagnoses of coronary artery stenosis ≥ 50% based on segment, vessel, or patient in the experimental and control groups

	Experimental group			Control group			*P*		
	Segment	Vessel	Patient	Segment	Vessel	Patient	Segment	Vessel	Patient
Number, *n*	263	64	18	305	73	21			
TP	25	12	7	31	13	8	–	–	–
TN	230	48	9	267	55	10	–	–	–
FP	5	2	1	4	3	2	–	–	–
FN	3	2	1	3	2	1	–	–	–
Sensitivity	89.2% (25/28)	85.7% (12/14)	87.5% (7/8)	91.2% (31/34)	86.7% (13/15)	88.9% (8/9)	0.814	1	0.828
Specificity	97.4% (230/236)	96% (48/50)	90% (9/10)	98.5% (267/271)	94.8% (55/58)	83.3% (10/12)	0.683	1	0.214
PPV	83.3% (25/30)	85.7% (12/14)	87.5% (7/8)	88.6% (31/35)	81.3% (13/16)	80% (8/10)	0.308	0.446	0.188
NPV	98.7% (230/233)	96% (48/50)	90% (9/10)	98.8% (267/270)	96.5% (55/57)	90.9% (10/11)	1	1	1

ICA results were used as the diagnostic reference

TP true positive, *TN* true negative, *FP* false positive, *FN* false negative, *PPV* positive predictive value, *NPV* negative predictive value

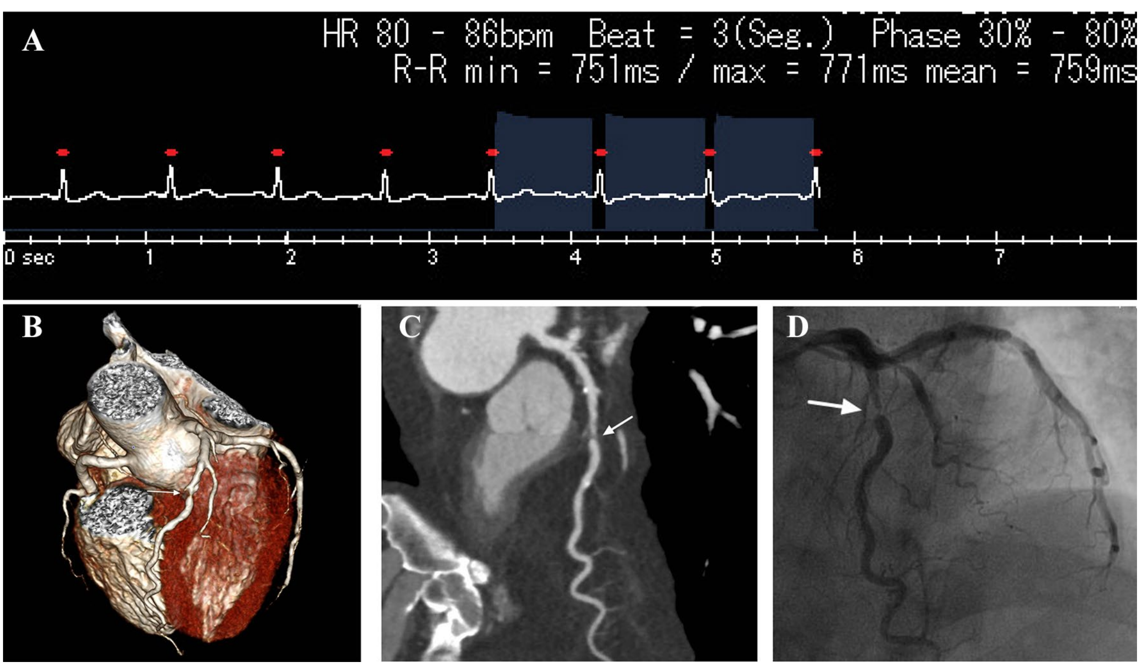

Fig. 2 A 69-year-old man with chest pain and AF in the control group, who had a BMI of 26.7 kg/m^2. **a** The ECG was recorded during data acquisition and 3 cardiac cycles were acquired, which showed that the HR was irregular (80–86 bpm). **b** The volume-rendering image showed severe stenosis of the proximal LAD branch (arrowhead). **c** The curved planar reconstruction image revealed proximal plaque and severe stenosis of the LAD branch (arrowhead). The image quality score was 4. **d** ICA confirmed 99% stenosis of the proximal LAD branch (arrowhead)

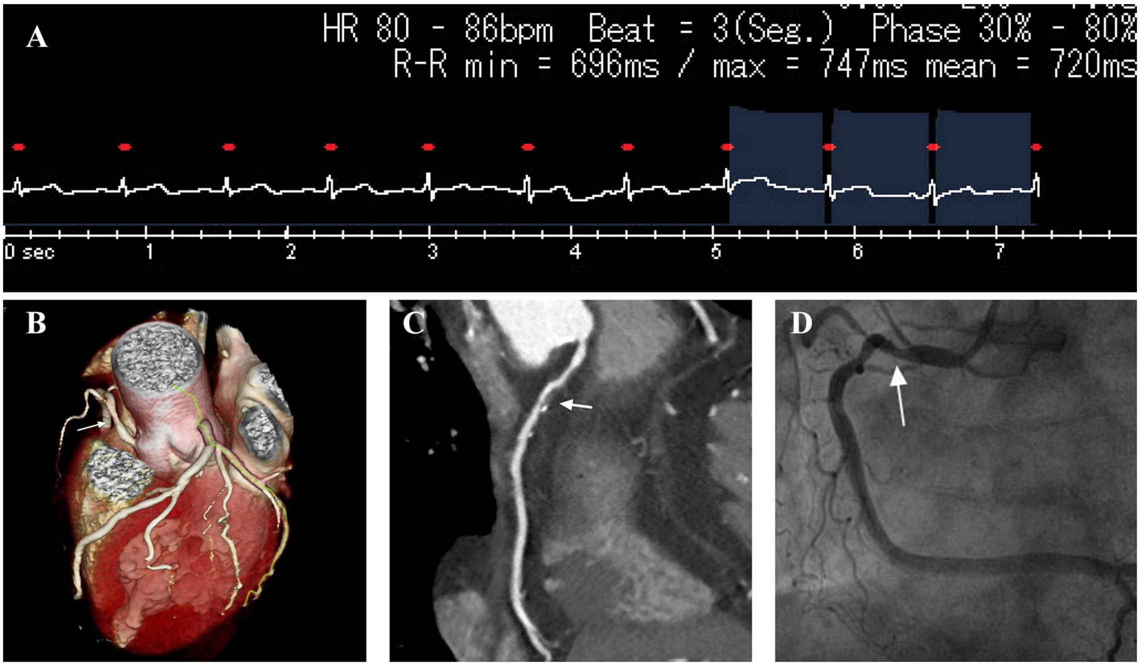

Fig. 3 A 67-year-old woman with chest pain and AF in the experimental group, who had a BMI of 25.8 kg/m^2. **a** The ECG was recorded during data acquisition and 3 cardiac cycles were acquired, which showed that the HR was irregular (80–86 bpm). **b** The volume-rendering image showed moderate stenosis of the proximal RCA (arrowhead). **c** The curved planar reconstruction showed proximal plaque and moderate stenosis of the proximal RCA (arrowhead). The image quality score was 3. **d** ICA confirmed 50% stenosis of the proximal RCA (arrowhead)

which is prone to cause or aggravate renal dysfunction, and even contrast nephropathy in severe cases [28, 29]. However, Cademartiri et al. [30] reported that, compared with a high concentration of contrast agent, a lower concentration significantly reduced the enhancement of the coronary artery, other factors being equal (dose and flow rate), and the CCTA image quality and diagnostic accuracy suffered [30, 31]. That is, a low concentration contrast agent can reduce the renal iodine load and the risk of contrast agent extravasation, but will also decrease the enhancement of target vessels.

Yet, low voltage scanning can make up for the deficiency in CT value; the average energy of an X-ray photon is much closer to the k-edge of iodine, and Compton scattering will decrease as CT value increases and radiation dose decreases. This provides a basis for the use of low concentration contrast agent [19, 32]. In CCTA, a high concentration contrast agent is not conducive to the display of calcified or non-calcified plaques [33]. In the present study, the same flow rate of contrast agent was used in the experimental and control groups, while the dose was individualized according to the BMI. Although the total iodine intake in the experimental group was reduced by 28.1%, the CT values of each branch of the coronary artery were > 250 HU on low voltage scanning and met the diagnostic requirements [34].

The results of the present study further confirmed the role of low-kV scanning for increasing the CT value of vessels. Several techniques were used in the experimental group to reduce the radiation dose, including axial volume scanning, low-tube voltage (100 kV), prospective gated data acquisition, and 3D-AIDR reconstruction algorithm. The effective dose of the experimental group (4.72 mSv) was 56.1% lower than that of the control group (10.76 mSv), both of which were significantly lower than previous reports of 13.0 mSv and 9.52 mSv using 320-spiral CT in CCTA for patients with AF [11, 35].

A higher FOM value reflects a superior CT image [36]. In the present study, the CNR of the coronary artery in the experimental group was not significantly lower than that of the control group, but the FOM value was higher because the effective radiation dose was less. This suggests that using a 100-kV tube voltage can improve the CCTA image. Because the radiation dose is proportional to the square of the tube voltage, adopting low-tube voltage is an effective method to reduce the radiation dose during CCTA [21]. However, low-kV scanning can increase image noise and artifacts and reduce image quality, which limits its clinical practicality.

The 3D-AIDR algorithm can greatly improve the speed of image reconstruction, reduce the artifact and noise, and improve the SNR and CNR [18, 19, 37]. In the present study, 50% AIDR values were used to control image noise and improve image quality, as medium-strength iteration values are generally recommended [19, 38]. The current study also adopted a low-tube voltage scanning protocol combined with 3D-AIDR in the experimental group, and compared with the control (120 kV scanning with filtered back projection reconstruction), the SNR and CNR were similar. There was also no significant difference in image quality, which is consistent with the results of Hara et al. [38] and Moscariello et al. [39].

The one single heartbeat acquisition, and the removal of stair-step artifacts, gives 320-spiral CT an advantage in CCTA of patients with arrhythmia. In the present study, 94.7% of the coronary artery segments met the diagnostic criteria of CAD. The time resolution of the first generation of 320-spiral CT was 175 ms, which was insufficient for patients with high HR, as motion artifacts could occur. Only multiple cardiac cycle acquisitions and multi-sector reconstruction methods can increase the effective time resolution [35]. For patients with AF, if the HR is higher than 65 bpm, multiple cardiac cycle acquisitions and multi-sector reconstruction are required. For a portion of the patients in the current study, up to 4 cardiac cycle reconstructions were necessary because of a fast HR, and absolute phase reconstruction at the end-systole was the best mode of reconstruction. As the HR increases, the radiation dose of patients in this study also increases. This is consistent with other reports [40].

The present results showed that motion artifacts mainly affected the middle and distal segment of the RCA, and distal segment of the LAD. The proximal segments of the LMA, LAD, and RCA, and LCX were the least affected segments, with the best image quality. This may be because of the relatively small vessels at the distal segment, poor filling with contrast agent, close proximity to the apex of the heart, and relatively large movements of the diaphragm muscle.

Although CCTA has good consistency with ICA for the diagnosis of CAD [30], with the advancement of technology, CCTA has become more and more widely used in patients with AF. The present study suggests that, relative to ICA, low-voltage and low-concentration contrast agent and prospective ECG gate scanning for CCTA in patients with AF had high sensitivity and specificity for diagnosing vascular stenosis $\geq 50\%$. This is in accord with other studies [41]. The preliminary results that we report here warrant further exploration of the clinical application of 320-spiral CT for patients with AF.

There are several limitations in this study. First, the number of patients was small, and a larger study population is needed to study further the image quality of patients with AF. Second, all of the images were reconstructed, and we did not investigate an association between radiation dose and image quality and HR or heart rhythm. Third, we did not consider the effect of BMI on the results. The BMIs of the subjects in this study were < 25, and therefore these findings may not be applicable to patients who are overweight or obese (BMI > 25). Finally, the calcification scores were not included in this study, as our CT scanner does not include a sequence for scanning calcification scores.

In conclusion, 320-spiral CT with prospective ECG gating, and isotonic low-concentration contrast agent combined with low-voltage scanning to perform CCTA, is feasible for patients with AF. This method for CCTA can significantly reduce radiation dose and iodine intake without sacrificing image quality, and improve the accuracy for diagnosing CAD.

Acknowledgements This work was supported by the Huimin Project of Science and Technology of Ningbo City (2016C51013), the Project of Medical and Health Technology Program in Zhejiang Province (2018KY155), and the Research Foundation of Hwa Hospital, University of Chinese Academy of Science, China (2019HMKY41). The present study was supported by the Ningbo Science and Technology Innovation Team Program (2014B82002), the Fang Runhua Fund of Hong Kong, and the KC Wong Magna Fund of Ningbo University.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This prospective study was approved by the Ethics Committee of Ningbo First Hospital. All procedures performed in studies involving human participants were in accordance with the Ethical Standards of the Institutional and/or National Research Committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Written informed consent was obtained from all individual participants included in the study.

References

1. Sun Z, Jiang W (2006) Diagnostic value of multislice computed tomography angiography in coronary artery disease: a meta-analysis. Eur J Radiol 60:279–286
2. Tsiflikas I, Drosch T, Brodoefel H et al (2010) Diagnostic accuracy and image quality of cardiac dual-source computed tomography in patients with arrhythmia. Int J Cardiol 143:79–85
3. Nucifora G, Schuijf JD, Tops LF et al (2009) Prevalence of coronary artery disease assessed by multislice computed tomography coronary angiography in patients with paroxysmal or persistent atrial fibrillation. Circ Cardiovasc Imaging 2:100–106
4. Fuster V, Ryden LE, Cannom DS et al (2011) 2011 ACCF/AHA/HRS focused updates incorporated into the ACC/AHA/ESC 2006 guidelines for the management of patients with atrial fibrillation: a report of the American College of Cardiology Foundation/American Heart Association Task Force on practice guidelines. Circulation 123:e269–e367
5. Clayton B, Roobottom C, Morgan-Hughes G (2015) CT coronary angiography in atrial fibrillation: a comparison of radiation dose and diagnostic confidence with retrospective gating vs prospective gating with systolic acquisition. Br J Radiol 88:20150533
6. Srichai MB, Barreto M, Lim RP, Donnino R, Babb JS, Jacobs JE (2013) Prospective-triggered sequential dual-source end-systolic

coronary CT angiography for patients with atrial fibrillation: a feasibility study. J Cardiovasc Comput Tomogr 7:102–109
7. Wang Q, Qin J, He B, Zhou Y, Yang JJ, Hou XL, Yang XB, Chen JH, Chen YD (2013) Computed tomography coronary angiography with a consistent dose below 2 mSv using double prospectively ECG-triggered high-pitch spiral acquisition in patients with atrial fibrillation: initial experience. Int J Cardiovasc Imaging 29:1341–1349
8. Xu L, Yang L, Zhang Z, Wang Y, Jin Z, Zhang L, Lu G (2013) Prospectively ECG-triggered sequential dual-source coronary CT angiography in patients with atrial fibrillation: comparison with retrospectively ECG-gated helical CT. Eur Radiol 23:1822–1828
9. Vorre MM, Abdulla J (2013) Diagnostic accuracy and radiation dose of CT coronary angiography in atrial fibrillation: systematic review and meta-analysis. Radiology 267:376–386
10. Oda S, Honda K, Yoshimura A et al (2016) 256-Slice coronary computed tomographic angiography in patients with atrial fibrillation: optimal reconstruction phase and image quality. Eur Radiol 26:55–63
11. Dewey M, Zimmermann E, Deissenrieder F, Laule M, Dubel HP, Schlattmann P, Knebel F, Rutsch W, Hamm B (2009) Noninvasive coronary angiography by 320-row computed tomography with lower radiation exposure and maintained diagnostic accuracy: comparison of results with cardiac catheterization in a head-to-head pilot investigation. Circulation 120:867–875
12. Kondo T, Kumamaru KK, Fujimoto S, Matsutani H, Sano T, Takase S, Rybicki FJ (2013) Prospective ECG-gated coronary 320-MDCT angiography with absolute acquisition delay strategy for patients with persistent atrial fibrillation. Am J Roentgenol 201:1197–1203
13. Korhonen M, Parkkonen J, Hedman M, Muuronen A, Onatsu J, Mustonen P, Vanninen R, Taina M (2017) Morphological features of the left atrial appendage in consecutive coronary computed tomography angiography patients with and without atrial fibrillation. PLoS ONE 12:e0173703
14. Rybicki FJ, Otero HJ, Steigner ML et al (2008) Initial evaluation of coronary images from 320-detector row computed tomography. Int J Cardiovasc Imaging 24:535–546
15. Pasricha SS, Nandurkar D, Seneviratne SK, Cameron JD, Crossett M, Schneider-Kolsky ME, Troupis JM (2009) Image quality of coronary 320-MDCT in patients with atrial fibrillation: initial experience. Am J Roentgenol 193:1514–1521
16. Hoe J, Toh KH (2009) First experience with 320-row multidetector CT coronary angiography scanning with prospective electrocardiogram gating to reduce radiation dose. J Cardiovasc Comput Tomogr 3:257–261
17. Slovis TL (2002) The ALARA concept in pediatric CT: myth or reality? Radiology 223:5–6
18. Di Cesare E, Gennarelli A, Di Sibio A, Felli V, Splendiani A, Gravina GL, Barile A, Masciocchi C (2014) Assessment of dose exposure and image quality in coronary angiography performed by 640-slice CT: a comparison between adaptive iterative and filtered back-projection algorithm by propensity analysis. Radiol Med 119:642–649
19. Yoo RE, Park EA, Lee W, Shim H, Kim YK, Chung JW, Park JH (2013) Image quality of adaptive iterative dose reduction 3D of coronary CT angiography of 640-slice CT: comparison with filtered back-projection. Int J Cardiovasc Imaging 29:669–676
20. Oda S, Utsunomiya D, Funama Y, Awai K, Katahira K, Nakaura T, Yanaga Y, Namimoto T, Yamashita Y (2011) A low tube voltage technique reduces the radiation dose at retrospective ECG-gated cardiac computed tomography for anatomical and functional analyses. Acad Radiol 18:991–999
21. Pan YN, Li AJ, Chen XM, Wang J, Ren DW, Huang QL (2016) Coronary computed tomographic angiography at low concentration of contrast agent and low tube voltage in patients with obesity: a feasibility study. Acad Radiol 23:438–445
22. Wu Q, Wang Y, Kai H, Wang T, Tang X, Wang X, Pan C (2016) Application of 80-kVp tube voltage, low-concentration contrast agent and iterative reconstruction in coronary CT angiography: evaluation of image quality and radiation dose. Int J Clin Pract 70(Suppl 9B):B50–B55
23. Zhang C, Yu Y, Zhang Z, Wang Q, Zheng L, Feng Y, Zhou Z, Zhang G, Li K (2015) Imaging quality evaluation of low tube voltage coronary CT angiography using low concentration contrast medium. PLoS ONE 10:e0120539
24. Austen WG, Edwards JE, Frye RL, Gensini GG, Gott VL, Griffith LS, McGoon DC, Murphy ML, Roe BB (1975) A reporting system on patients evaluated for coronary artery disease. Report of the Ad Hoc Committee for Grading of Coronary Artery Disease, Council on Cardiovascular Surgery, American Heart Association. Circulation 51:5–40
25. Shuman WP, Branch KR, May JM, Mitsumori LM, Lockhart DW, Dubinsky TJ, Warren BH, Caldwell JH (2008) Prospective versus retrospective ECG gating for 64-detector CT of the coronary arteries: comparison of image quality and patient radiation dose. Radiology 248:431–437
26. Cury RC, Abbara S, Achenbach S et al (2016) CAD-RADS(TM) Coronary artery disease—reporting and data system. An expert consensus document of the Society of Cardiovascular Computed Tomography (SCCT), the American College of Radiology (ACR) and the North American Society for Cardiovascular Imaging (NASCI). Endorsed by the American College of Cardiology. J Cardiovasc Comput Tomogr 10:269–281
27. Ahmadi N, Nabavi V, Hajsadeghi F, Flores F, French WJ, Mao SS, Shavelle D, Ebrahimi R, Budoff M (2011) Mortality incidence of patients with non-obstructive coronary artery disease diagnosed by computed tomography angiography. Am J Cardiol 107:10–16
28. Zhao Y, Tao Z, Xu Z et al (2011) Toxic effects of a high dose of non-ionic iodinated contrast media on renal glomerular and aortic endothelial cells in aged rats in vivo. Toxicol Lett 202:253–260
29. Xue X, Jiang L, Duenninger E, Muenzel M, Guan S, Fazakas A, Cheng F, Illnitzky J, Keil T, Yu J (2018) Impact of chronic kidney disease on Watchman implantation: experience with 300 consecutive left atrial appendage closures at a single center. Heart Vessels 33:1068–1075
30. Cademartiri F, Mollet NR, van der Lugt A, McFadden EP, Stijnen T, de Feyter PJ, Krestin GP (2005) Intravenous contrast material administration at helical 16-detector row CT coronary angiography: effect of iodine concentration on vascular attenuation. Radiology 236:661–665
31. Neefjes LA, Dharampal AS, Rossi A et al (2011) Image quality and radiation exposure using different low-dose scan protocols in dual-source CT coronary angiography: randomized study. Radiology 261:779–786
32. Wang R, Schoepf UJ, Wu R, Reddy RP, Zhang C, Yu W, Liu Y, Zhang Z (2012) Image quality and radiation dose of low dose coronary CT angiography in obese patients: sinogram affirmed iterative reconstruction versus filtered back projection. Eur J Radiol 81:3141–3145
33. Leber AW, Becker A, Knez A et al (2006) Accuracy of 64-slice computed tomography to classify and quantify plaque volumes in the proximal coronary system: a comparative study using intravascular ultrasound. J Am Coll Cardiol 47:672–677
34. Yamamuro M, Tadamura E, Kanao S, Wu YW, Tambara K, Komeda M, Toma M, Kimura T, Kita T, Togashi K (2007) Coronary angiography by 64-detector row computed tomography using low dose of contrast material with saline chaser: influence of total injection volume on vessel attenuation. J Comput Assist Tomogr 31:272–280

35. Xu L, Yang L, Fan Z, Yu W, Lv B, Zhang Z (2011) Diagnostic performance of 320-detector CT coronary angiography in patients with atrial fibrillation: preliminary results. Eur Radiol 21:936–943
36. Schindera ST, Nelson RC, Mukundan S Jr, Paulson EK, Jaffe TA, Miller CM, DeLong DM, Kawaji K, Yoshizumi TT, Samei E (2008) Hypervascular liver tumors: low tube voltage, high tube current multi-detector row CT for enhanced detection—phantom study. Radiology 246:125–132
37. Zhang WL, Li M, Zhang B, Geng HY, Liang YQ, Xu K, Li SB (2013) CT angiography of the head-and-neck vessels acquired with low tube voltage, low iodine, and iterative image reconstruction: clinical evaluation of radiation dose and image quality. PLoS ONE 8:e81486
38. Hara AK, Paden RG, Silva AC, Kujak JL, Lawder HJ, Pavlicek W (2009) Iterative reconstruction technique for reducing body radiation dose at CT: feasibility study. Am J Roentgenol 193:764–771
39. Moscariello A, Takx RA, Schoepf UJ et al (2011) Coronary CT angiography: image quality, diagnostic accuracy, and potential for radiation dose reduction using a novel iterative image reconstruction technique-comparison with traditional filtered back projection. Eur Radiol 21:2130–2138
40. Rist C, Johnson TR, Muller-Starck J et al (2009) Noninvasive coronary angiography using dual-source computed tomography in patients with atrial fibrillation. Investig Radiol 44:159–167
41. Leschka S, Stolzmann P, Desbiolles L et al (2009) Diagnostic accuracy of high-pitch dual-source CT for the assessment of coronary stenoses: first experience. Eur Radiol 19:2896–2903