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Achieving low radiation dose and contrast agents dose in coronary CT angiography at 60-kVp ultra-low tube voltage

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Abstract

Objectives To explore the feasibility of a one-beat protocol and ultra-low tube voltage of 60 kVp in coronary CT angiography (CCTA).

Methods This prospective study enrolled 107 patients (body mass index ≤ 26 kg/m^2) undergoing CCTA examinations. Specifically, the conventional group (n = 52) underwent 100 kVp scanning with 45 ml iodine contrast agent and 4 ml/s injection rate, and the low-dose group (n = 55) underwent 60 kVp scanning with 28 ml iodine contrast agent and 2.5 ml/s injection rate. The CT value, signal-noise-ratio (SNR), contrast-noise-ratio (CNR) and subjective image quality score of two groups in aorta (AO), right coronary artery (RCA), left anterior descending (LAD) and left circumflex (LCX) are analyzed in this study. Three types of radiation doses [i.e., volume CT dose index (CTDIvol), dose length product (DLP), effective dose (ED)] of two groups are also compared.

Results The quantitative results indicated that the low-dose group achieved higher CT values, SNR and CNR results of the AO than the conventional group (P values < 0.001). Both groups had similar CT values, SNR and CNR results in RCA, LAD, and LCX (P values > 0.05). A good agreement is noted with respect to subjective image quality scores in both groups, while the Cohen's kappa value is 0.815 in the low-dose group and 0.825 in the conventional group, respectively. In addition, the radiation dose of the low-dose group is significantly lower than the conventional group in terms of CTDIvol, DLP and ED values, and the contrast dose in the low-dose group is also significantly reduced compared to the conventional group (P values < 0.001).

Conclusions One-beat protocol with an ultra-low tube voltage of 60 kVp could provide improved coronary image quality, reduced radiation dose and reduced iodine contrast dose.

Keywords Coronary CT angiography, Contrast agent, Radiation dose

Feng Huang and Xi Wu co-supervised this work.

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Introduction

Cardiovascular disease (CVD) is a type of disease involving the heart or blood vessels, including the coronary artery disease (CAD), stroke, heart failure, hypertensive heart disease, aortic aneurysm, thromboembolic disease and venous thrombosis. The potential pathogenesis is various, such as hypertension, diabetes, high cholesterol, obesity, exercise, and excessive drinking [1–4] etc. The China Cardiovascular Health and Disease Report 2022 [5] reveals that CVD accounted for 45.86% of all deaths in urban and 48.00% of all deaths in rural China, which occupies the top spot in the composition of disease deaths in 2020. The ischemic heart disease, ischemic stroke, and hemorrhagic stroke are three main factors of cardiovascular death in China. It is estimated that there are about 330 million CVD patients, including 11.39 million with coronary heart disease in China in 2023. Meanwhile, globally from 1990 to 2022, the age-standardized mortality rate of CVD decreased by 34.9%, dropping from 358.4 to 233.2 cases per 100,000 people. However, the total number of deaths caused by CVD increased from 12.4 to 19.8 million during the same period [6]. This data reflects global population growth and aging, while also highlighting the impact of preventable metabolic, behavioral, and environmental risk factors on public health.

Coronary digital subtraction angiography (DSA) is the gold standard for diagnosing CAD. However, this technique is invasive and expensive [7]. The coronary CT angiography (CCTA) is fast, complicated and relatively inexpensive, and then gradually becoming an important clinical diagnostic tool and a preferred technique for safe and reliable CAD screening [8]. Nevertheless, CCTA is associated with the high radiation dose problem and the ensuing cancer risk induced by ionizing radiation, which may limiting its further promotion and application in routine screening [9, 10]. The American Heart Association issued a statement concluding that the CT radiation dose of 10 mSv can lead to the malignancy for 1 in 2,000 patients undergoing CT examination [11]. Therefore, reducing radiation dose while maintaining CCTA image quality has become a research hotspot [12–14].

The high radiation dose associated with CCTA is one of the key issues limiting its further promotion and application in routine screening [9, 10]. CT radiation dose is closely related to scanning parameters. Currently, two CCTA examination technologies to reduce radiation, i.e., the low tube voltage scheme with 70 kVp [15] and automatic tube voltage scheme [8], can effectively reduce radiation dose compared to the conventional scanning with 120 kVp tube voltage In order to explore whether it is possible for the scanning tube voltage to be further reduced in CCTA, we evaluated the image quality of the CCTA data acquired from the 60 kVp tube voltage combined with the One-beat (free heart imaging) scanning protocol and the iterative Karl-3D reconstruction algorithm in this study. Additionally, we also assess the feasibility to reduce the contrast agent dose in the CCTA examination. This low radiation dose and low contrast agent dose scheme is potential to be a new reference for clinical CCTA examination.

Materials and methods

Study participants

This study prospectively collected 107 patients from Hunan Provincial People's Hospital (the First Affiliated Hospital of Hunan Normal University), who underwent the CCTA examination between January 2024 and August 2024. Inclusion criteria were: (1) body mass index (BMI) ≤ 26 kg/m^2; (2) suspected CAD; (3) good vascular conditions, tolerating contrast injection rate of 2.5 to 4 ml/s. Exclusion criteria were: (1) severe arrhythmia, heart failure, and severe hepatic/renal insufficiency; (2) history of coronary artery bypass graft and / or pacemaker implantation; (3) pregnant or lactating women; (4) individuals who cannot use nitroglycerin. All subjects are divided into two groups: Group A (conventional group) adopts the 100 kVp tube voltage combined with the iodine contrast injection rate of 4 ml/s and the volume of 45 ml; Group B (low-dose group) adopts the 60 kVp tube voltage combined with the iodine contrast injection rate of 2.5 ml/s and the volume of 28 ml (Fig. 1). Both groups use the One-beat (free heart imaging) protocol and the iterative Karl-3D reconstruction algorithm for CCTA.

This study was approved by the Ethics Committee of Hunan Provincial People's Hospital and conducted according to the Declaration of Helsinki. All patients received an iodine contrast questionnaire to ensure no contraindications to intravenous iodine contrast and signed informed consents.

CCTA protocol

All subjects underwent the CCTA examination on the 320-row, 16-cm wide detector CT scanner (uCT 960+, United Imaging Healthcare, Shanghai, China). Before the examination, all patients were trained to hold their breath and sublingually administered with 0.5 mg of nitroglycerin. The tube voltage is set to 100 kVp for the conventional group and 60 kVp for the low- dose group. For both groups, the effective tube current is 229 mAs with 140 mm collimation width and 0.25 s rotation time. The reconstructed image size is 512×512, and the reconstruction thickness is 0.5 mm. Non-ionic contrast (iomeprol, 400 mgI/ml) was injected within 11.2 s. The conventional group used the injection rate of 4 ml/s and the contrast agent dose of 45 ml. The low-dose group used the injection rate of 2.5 ml/s and the contrast agent dose of 28 ml. A vascular threshold trigger technique

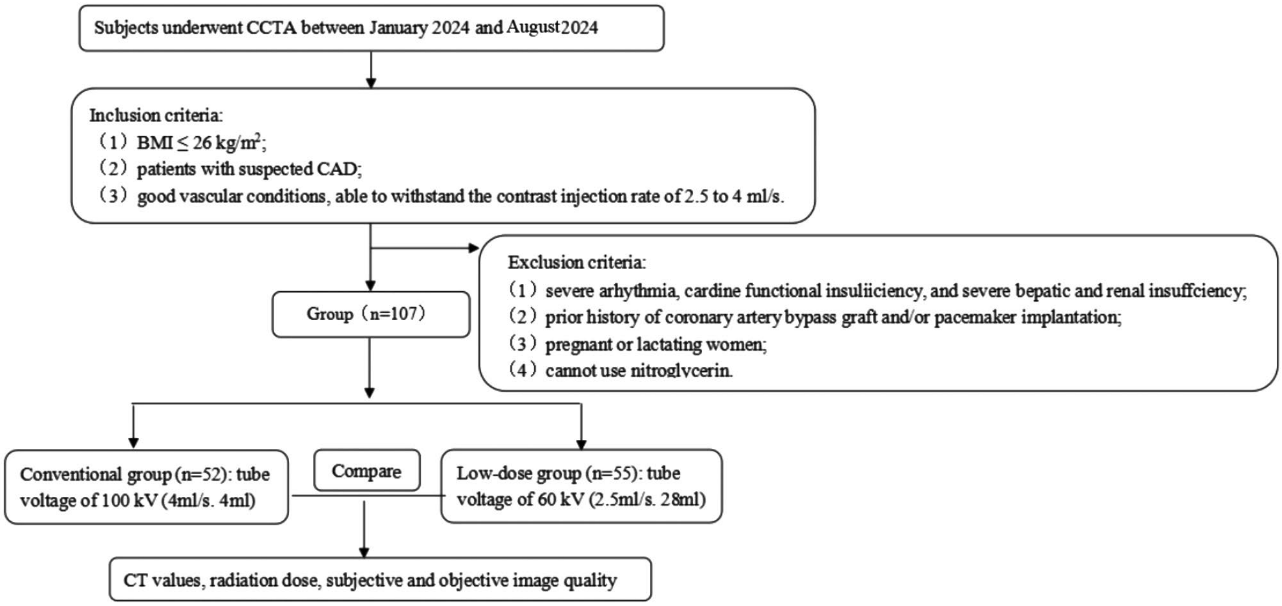

Fig. 1 Flowchart of the study design. BMI, body mass index; CCTA, coronary CT angiography; CAD, coronary artery disease

(tracking the descending aorta) was used with the CT value threshold of 180 HU and a 2 s delay for the automatic CCTA scan.

Image analysis

The sex, age, BMI values, volume CT dose index (CTDIvol), and dose length product (DLP) of all subjects are included in the statistical analysis. The effective dose (ED) for the patient was calculated as the product of the DLP in mGy·cm multiplied by a conversion coefficient of 0.014·mSv/(mGy·cm).

Objective assessment

The CT values in the aortic (AO) root, left anterior descending branch (LAD), right coronary artery (RCA), and left circumflex (LCX) were measured, with the region of interest set to at least half the vessel diameter, measurements were taken three times and averaged to evaluate the CT value accuracy. The standard deviation (SD) of the CT value in chest wall muscle and vessels is measured to evaluate the CCTA image noise level. The following equations were used to calculate signal-noise-ratio (SNR) and contrast-noise-ratio (CNR):

$$SNR = Mean\left(CT_{vessel}\right)/SD_{vessel}$$

$$CNR = \left(CT_{vessel} - CT_{muscle}\right)/SD_{muscle}$$

Subjective image analysis

Two radiologists with over 5 years of experience in CCTA diagnosis independently evaluated all images according to the 1–5 point scoring system recommended by the American Heart Association (AHA). They rated the images subjectively based on noise levels, motion artifacts, vessel attenuation, edge sharpness and overall image quality. Scoring criteria were: 1 for non-diagnostic image quality, excessive noise, inadequate vessel attenuation and indistinct margin; 2 for poor image quality, high noise, low attenuation and blurred margin; 3 for moderate image quality, moderate noise, sufficient attenuation and good margin; 4 for good image quality, mild noise, good attenuation and clear margin; 5 for excellent image quality, minimal noise, high attenuation and clear margin. Images scoring 3 or above were deemed acceptable for diagnosis. For each vessel, segments over 1.5 mm were assessed and the lowest score was taken as the vessel's image quality score. The minimum score among the three major coronary arteries (RCA, LAD, and LCX) was used as the overall image quality score for the patient [15]. Raw scores from both raters were used for the agreement assessment, while the subjective image quality scores from both raters were negotiated and used for comparisons between patient groups.

Statistical analysis

All statistical analyses were performed using SPSS software (version 22.0). The Kolmogorov-Smirnov was used to test normality of count data, which were expressed as mean ± SD, the normally-distributed data is compared by using Student's t-test; the non-normally distributed data is compared by using Mann-Whitney test for median with 25–75% interquartile range. Categorical variables were expressed as numbers and then compared by using chi-square or Fisher's exact test, as appropriate. Cohen's

Table 1 Baseline characteristics

	Conventional group ($n=52$)	Low-dose group ($n=55$)	t-value/χ^2	*P*-value
Age	63.46 ± 9.729	64.47 ± 11.883	-0.480	0.632
Male/Female	24/28	23/32	0.204	0.652
BMI (kg/m^2)	22.71 ± 2.403	22.59 ± 2.228	0.259	0.796
Heart rate (beats/minute)	79.36 ± 13.049	78.02 ± 13.841	0.493	0.623
Coronary dominance				0.485
Right-sided	50	52		
Left-sided	1	3		
Codominant	1	0		
CAD-RADS score				0.184
0	18	15		
1	9	3		
2	9	18		
3	10	11		
4 A	4	7		
4B	2	1		
Cardiovascular risk factors				0.422
Hypertension, n	21	25		
Diabetes mellitus, n	8	8		
Hyperlipidemia, n	8	4		
hepatic adipose infiltration, n	5	2		

Notes: BMI, body mass index; CAD-RADS, Coronary Artery Disease-Reporting and Data System. Coronary dominance, CAD-RADS score, and Cardiovascular risk factors data were conducted using Fisher's exact test

Table 2 Comparison of the subjective ratings of image quality in the two groups

Score	Conventional group ($n=52$)		Low-dose group ($n=55$)	
	Rater 1	Rater 2	Rater 1	Rater 2
5	37	40	38	42
4	10	8	15	11
3	5	4	2	2
Kappa value	0.815		0.825	

Kappa test was used to assess inter-rater agreement. P-value < 0.05 is considered statistically significance.

Results

Table 1 list all characteristics of general and clinical information for the two groups. It can be seen that there is no significant difference between the two groups (P value ≥ 0.05).

Subjective image analysis

It can be observed that there is no significant difference for the subjective image quality scores between the conventional group (Z=-0.661, P value = 0.509) and the low-dose group (Z=-0.817, P value = 0.414) based on the Mann-Whitney test. Good enhancements were obtained for all coronary artery branches. The two reviewers judged that Cohen's kappa coefficient was 0.815 (95% CI 0.729–0.901) in the conventional group (P value < 0.001) and was 0.825 (95% CI 0.741–0.909) in the low-dose group, indicating a good agreement in both groups (P value < 0.001), as shown in Table 2. Typical examples are shown in Fig. 2.

Objective assessment

The CT values, SNR and CNR of AO, RCA, LAD, and LCX in the low-dose group were higher than that in the conventional group. However, except for the AO, the CT value, SNR and CNR results of RCA, LAD, and LCX between these two groups were not statistically significant (P-value > 0.05), as shown in Table 3.

Radiation dose

CTDlvol, DLP, and ED of the conventional group were higher than that of the low-dose group (all $P < 0.001$), as shown in Table 4.

Discussion

This study explored the feasibility of using a lower tube voltage of 60 kVp for patients with BMI ≤ 26 kg/m^2 in CCTA. Some previous studies have validated that the low tube voltage of 70 kVp could help to reduce the radiation dose for these subjects with BMI ≤ 26 kg/m^2 [8, 15]. Furthermore, compared to invasive coronary angiography (ICA), this 70 kVp setting demonstrated high diagnostic accuracy in identifying stenosis [16]. However, there is still no a study discussing whether using the CCTA protocol with a lower tube voltage of 60 kVp can effectively reduce the radiation dose for these subjects with BMI ≤ 26 kg/m^2. Furthermore, we found that the CCTA

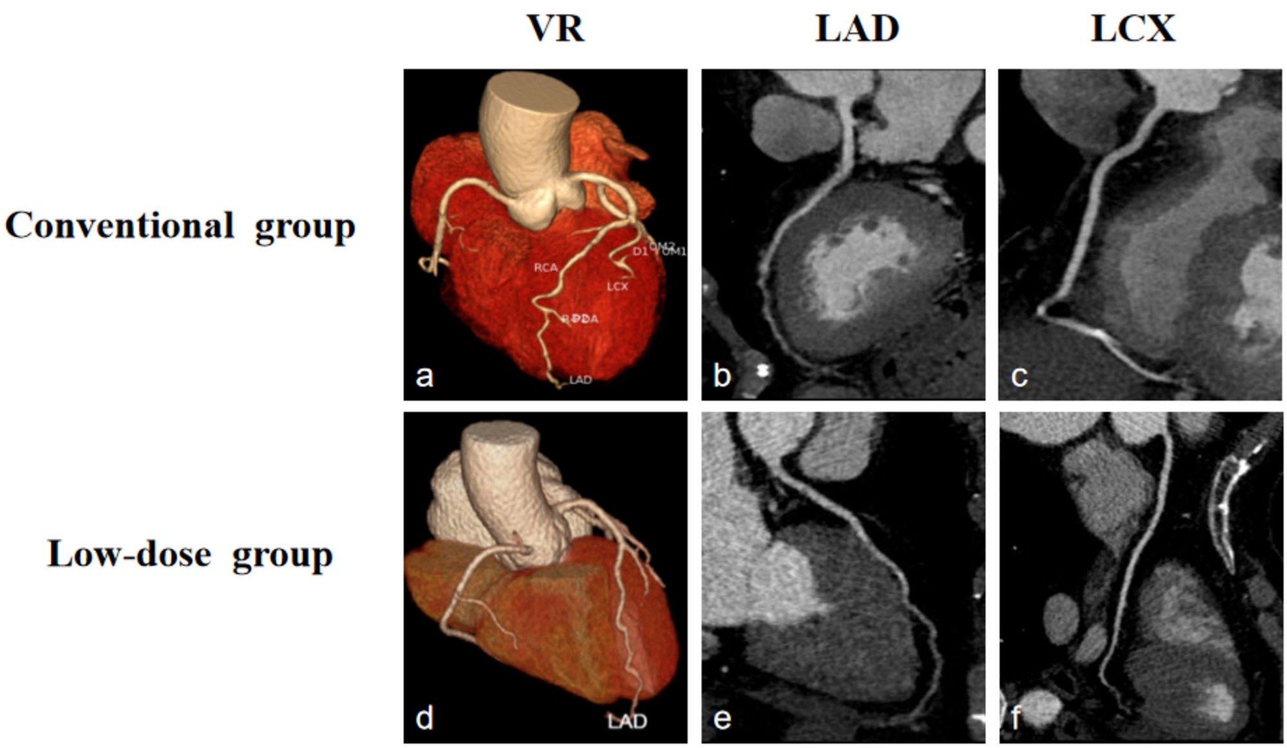

Fig. 2 Comparison of image quality between two groups. Figure **a-c**: Patient in conventional group, BMI = 20.0 kg/m^2, tube voltage 100 kVp, contrast dose 45 ml, image quality score 5, mean CT of inter-chest wall muscles 68.33 HU, noise value 14.01 HU, ED 3.65 mSv. Figure **d-f**: Patient in low-dose group, BMI = 21.3 kg/m^2, tube voltage 60 kVp, contrast dose 28 ml, image quality score 5, mean CT value between chest wall muscles 66.33 HU, noise value 13.89 HU, ED 0.41 mSv. Note: VR, volume rendering; LAD, left anterior descending artery; LCX, left circumflex

Table 3 Comparison of the objective image quality between the two groups

	Conventional group (*n* = 52)	Low-dose group (*n* = 55)	t-value	*P*-value
CT value (HU)				
AO	434.135 ± 117.233	495.611 ± 94.318	-2.997	0.003
RCA	406.564 ± 123.872	443.310 ± 92.691	-1.744	0.084
LCX	390.082 ± 134.237	432.328 ± 100.819	-1.816	0.072
LAD	409.565 ± 122.504	442.194 ± 89.278	-1.581	0.117
Chest wall muscles	61.827 ± 8.891	62.733 ± 11.807	-0.447	0.656
SNR				
AO	26.284 ± 6.101	31.131 ± 7.737	-3.585	0.001
RCA	24.346 ± 6.063	25.918 ± 6.796	-1.260	0.211
LCX	23.633 ± 6.100	23.645 ± 6.240	-0.010	0.992
LAD	24.245 ± 5.585	25.563 ± 6.873	-1.084	0.281
CNR				
AO	27.279 ± 6.747	33.441 ± 7.127	-4.587	< 0.001
RCA	25.209 ± 7.504	29.249 ± 7.0270	-2.876	0.005
LCX	24.503 ± 7.797	28.526 ± 7.494	-2.721	0.008
LAD	25.480 ± 7.483	29.230 ± 6.673	-2.739	0.007

Note: CNR, contrast-to-noise ratio; SNR, signal-to-noise ratio; AO, aorta; LAD, left anterior descending artery; LCX, left circumflex; RCA, right coronary artery

Table 4 Comparison of the radiation dose between the two groups

	Conventional group (*n* = 52)	Low-dose group (*n* = 55)	Z-value	*P*-value
CTDIvol (mGy)	20.783(19.029,23.129)	2.762(2.563,3.036)	-8.595	< 0.001
DLP (mGy*cm)	290.955(269.618,323.952)	38.670(35.880,41.960)	-8.913	< 0.001
ED (mSv)	4.073(3.775,4.535)	0.541(0.502,0.587)	-8.913	< 0.001

protocol with the low tube voltage of 60 kVp can also contribute to the reduction of contrast agent dose.

Due to the characteristics of X-rays, the literature on CCTA examination at a tube voltage of 70 kVp [8] indicates the feasibility of a contrast injection flow rate of 3 ml/s and a dose of 33 ml, with the contrast injection rate and dose positively correlated with the tube voltage. Therefore, a lower tube voltage of 60 kVp could consider a lower contrast dose (28 ml) and an injection flow rate (2.5 ml/s), reducing the likelihood of adverse reactions and radiological adverse events caused by iodinated contrast agents [17, 18] compared to the conventional CCTA examination. Due to the temporal resolution limitations of CT hardware, CCTA often experiences motion artifacts from cardiac pulsation in practical applications, compromising image quality and diagnostic accuracy. In routine clinical procedures, although pharmacological heart rate control is used to improve CCTA success rates, its effectiveness is limited. To address these issues, United Imaging Healthcare has developed an AI-based motion artifact correction technology called the one-beat (free heart imaging) protocol, also known as cardiac freezing technology. The core algorithm, CardioCapture, leverages the superior learning capabilities of deep learning models to reduce motion artifacts in non-"optimal" CCTA images. This expands the range of evaluable images within the cardiac cycle, reducing clinical reliance on "optimal" images [19–21]. Traditional Filtered Back Projection (FBP) methods rely on several ideal assumptions. However, due to simplifications and approximations during data acquisition, FBP cannot fully account for measurement errors in non-ideal conditions, leading to amplified noise and artifacts in low-dose CT images. To reduce radiation dose while maintaining diagnostic accuracy, United Imaging Healthcare has introduced the Karl-3D hybrid iterative reconstruction technology. This technology significantly reduces image noise caused by low-dose scanning, thereby effectively improving image quality [22–25]. The peak energy of X-ray photons under the tube voltage of 60 kVp is close to the K-edge of contrast agent materials (33 keV for iodine) [26], enabling higher image contrast under the premise of reducing the total amount of iodine. However, the reduction of X-photons passing through the examined body usually results in a relatively poor SNR ratio. Therefore, the Karl-3D iteration algorithm is needed to improve the CCTA image quality, and the one-beat heart freezing technology is also used to reduce the interference of subject respiratory motion artifacts and further improve the CCTA image quality.

In this study, the average heart rates in the conventional dose group and the low-dose group were 79.36 ± 13.049 beats/minute and 78.02 ± 13.841 beats/minute, respectively. While these values are relatively high, relevant research findings indicate that even in cases of elevated heart rate or arrhythmia, CT scanners equipped with 16-cm wide detectors can still produce high-quality CCTA images while achieving low-dose radiation [27–28]. The equipment used in this study is also a CT scanner equipped with a 16-cm wide detector, thus possessing the potential to achieve the same objectives.

This study analyzed CCTA images of 107 subjects with BMI $\leq$ 26 kg/m^2. Results were: CT values, SNR and CNR results of AO, RCA, LAD and LCX in the low-dose group are higher than that in the conventional group. However, except for the AO, CT values, SNR and CNR results of RCA, LAD and LCX are not statistically significant between the two groups (P values > 0.05). Besides, there is no significant difference for the objective evaluation of coronary arteries (RCA, LAD, LCX) between the low-dose group and the conventional group, while objective image evaluation of AO in the low-dose group was slightly better than that in the conventional group, showing improved image quality compared to the conventional group. The Cohen's kappa coefficient of both groups are over 0.81, indicating there is an almost perfect agreement between two raters in both groups and there is no significant difference between these two groups in this study. Radiation dose of the conventional group is higher than that of the low-dose group. All dose indicators of the conventional group are significantly higher than that of the low-dose group, which is about 7.5 times that of the low-dose group (P values < 0.001). This fact indicates that the low-dose group could effectively reduce radiation dose compared to the conventional group.

The tube voltage is usually set to 120 kVp for the conventional CCTA examination based on common CT scanners, and it is reduced to 100 kVp in the high-end uCT960 + scanner. However, the corresponding ED value at 100 kVp tube voltage still remains around 4.073 mSv. In this study, the ED value can be controlled to 0.541 mSv for the uCT960 + to combined with 60 kVp tube voltage, One-beat (free-heart imaging) protocol and iterative Karl-3D reconstruction algorithm for CCTA examination, indicating a significantly effective radiation dose reduction for subjects. In the comparative study between the low-dose group (60 kVp) and the conventional-dose group (100 kVp), the total amount of iodine contrast agent used in the low-dose group and its injection rate were approximately only 62% of those in the conventional-dose group. Specifically, the volume of iodine contrast agent applied in the low-dose group was reduced from 45 ml to 28 ml, and the injection rate was adjusted from 4 ml/s to 2.5 ml/s. More importantly, no significant differences were observed between the low-dose group and the conventional-dose group in both subjective and objective assessments of image quality. This study utilized a high iodine contrast agent concentration

(400 mgI/mL) for CCTA scans at 60 kVp. Theoretically, a lower concentration could be used if the iodine delivery rate and total load remain the same, as the contrast effect should be similar [29, 30]. However, different concentrations of iodine contrast agents used in CCTA examinations at 60 kVp may necessitate recalculation of flow and volume, thus requiring further research to validate in practice.

It should be noted that this work has several limitations. For example, the number of selected subjects is small and the gold standard (DSA) is lacked. This study did not utilize the gold standard, Intracoronary Angiography (ICA), for reference comparison, which may lead to overestimation or underestimation in the evaluation of low-density coronary plaques. Further research is needed to validate the findings using ICA as a reference. Future research plans will consider incorporating ICA into the study scope.

In conclusion, One-beat protocol incorporating ultra-low tube voltage of 60 kVp scanning technology based on uCT960 + scanner can obtain a satisfactory CCTA image quality meeting clinical requirements. Given the reduction in radiation and contrast doses, this technological approach holds certain clinical application prospects for the initial screening of coronary heart disease.

Abbreviations

CCTA	Coronary CT angiography
SNR	Signal-noise-ratio
CNR	Contrast-noise-ratio
AO	Aorta
RCA	Right coronary artery
LAD	Left anterior descending
LCX	Left circumflex
CTDIvol	Volume CT dose index
DLP	Dose length product
ED	Effective dose
CVD	Cardiovascular disease
CAD	Coronary artery disease
DSA	Digital subtraction angiography
BMI	Body mass index
SD	Standard deviation
AHA	American Heart Association
FBP	Filtered Back Projection
ICA	Intracoronary Angiography

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Author contributions
HF and HWL conceived the ideas; designed the experiments. XA; WX; SWJ and HR performed the experiments. HWL; XA and WX analyzed the data. SWJ and HR provided critical materials. WX and HWL wrote the manuscript. HF and LP supervised the study. All the authors have read and approved the final version for publication.

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Data availability
The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The current research was ratified by the Medial Ethics Committee of Hunan Provincial People's Hospital (IRB Approval No: [2024]-46) and was conducted in accordance with Declaration of Helsinki. All patients had received a questionnaire on injection of iodine contrast agents to ensure no contraindications of intravenous injection with iodine contrast agent and signed the informed consent form.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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