

Coronary Coronary CT Angiography phase acquisition strategies in sinus arrhythmia: prospective evaluation of image quality and diagnostic accuracy

Naqin Wang

BenQ Medical Center, the Affiliated BenQ Hospital of Nanjing Medical University

Ling Ge

BenQ Medical Center, the Affiliated BenQ Hospital of Nanjing Medical University

Jing Liu

BenQ Medical Center, the Affiliated BenQ Hospital of Nanjing Medical University

Jiajie Zhu

BenQ Medical Center, the Affiliated BenQ Hospital of Nanjing Medical University

Yuxuan Zhu

BenQ Medical Center, the Affiliated BenQ Hospital of Nanjing Medical University

Wei Cai

BenQ Medical Center, the Affiliated BenQ Hospital of Nanjing Medical University

Yanhong Fang

BenQ Medical Center, the Affiliated BenQ Hospital of Nanjing Medical University

hongbing Ma

mhb_mj@126.com

BenQ Medical Center, the Affiliated BenQ Hospital of Nanjing Medical University

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Abstract

Objective

This study aimed to evaluate the impacts of absolute-phase and relative-phase acquisition protocols on image quality, interpretability and stenosis diagnostic accuracy in sinus arrhythmia patients undergoing prospectively ECG-triggered axial coronary CTA.

Materials and Methods

Consecutive patients with sinus arrhythmia between January 2022 and December 2024 were enrolled and randomly assigned into absolute-phase (Group B) and relative-phase (Group C) groups at a 1:1 ratio. With age, gender and baseline HRas covariates, propensity score matching was adopted to select matched patients with regular sinus rhythm as the control group (Group A). Objective and subjective image quality, the proportion of interpretable coronary segments, and diagnostic accuracy (using invasive coronary angiography as the gold standard, stenosis $\geq 50\%$ as the positive cutoff) were compared across three groups.

Results

No significant differences in objective image parameters were found. Subjective scores in Group A, B and C were 3.84 ± 0.61 , 3.76 ± 0.74 and 3.62 ± 0.92 (all $P < 0.001$). The rates of interpretable segments were 96.4%, 94.9% and 90.7%, with segment-based diagnostic accuracy of 93.1%, 95.8% and 88.9%, respectively ($P < 0.05$).

Conclusion

Increased heart rate variability aggravates coronary motion artifacts at moderate heart rates. Compared with relative-phase strategy, absolute-phase acquisition effectively reduces artifacts, and improves image interpretability and diagnostic performance in arrhythmic patients.

Key Points

- 1.Moderate heart rate with high heart rate variability aggravates coronary motion artifacts.
- 2.Absolute phase acquisition reduces coronary motion artifacts in relevant patients.
- 3.Absolute phase acquisition should be prioritized for patients with high heart rate variability.

1. Introduction

Prospective electrocardiogram-gated axial acquisition effectively reduces effective radiation dose, and is clinically recommended as the optimal scanning mode for coronary computed tomography angiography[1]. However, elevated heart rate variability (HRV) causes abnormal fluctuations in electrocardiographic R-R intervals, which markedly limits the clinical applicability of this protocol. Beta-blockers are routinely used to regulate heart rate(HR) and HRV in clinical practice. Nevertheless, due to absolute drug contraindications and poor individual drug response, high HRV cannot be effectively corrected preoperatively in some patients[2].

High HRV acts as an independent core trigger for coronary misregistration and pulsatile motion artifacts in coronary computed tomography angiography[3]. The mechanism of motion artifacts is directly linked to reconstruction phase mismatch mediated by elevated HRV. Excessive HRfluctuation throughout the cardiac cycle leads to continuous rapid displacement of coronary vessel walls. Mismatch between scanning speed and actual vascular movement results in blurred coronary contours and distorted details in the X-Y plane[3]. Currently, 16-cm full-coverage wide-detector systems have been widely applied. Single gantry rotation enables complete whole-heart volumetric data acquisition and eliminates Z-axis slice misregistration artifacts. Accordingly, the major quality control challenge for coronary computed tomography angiography in patients with high HRV lies in intractable X-Y plane motion artifacts. Such artifacts may mimic atherosclerotic plaques or conceal true coronary stenosis, thereby increasing the risks of misdiagnosis and missed diagnosis. Ultimately, they contribute to inappropriate clinical decisions and excessive medical resource consumption[4].

Evidence-based studies by Muenzel et al.[5] and Chen et al.[6] have confirmed that HRV fluctuations exert no significant impacts on coronary artifacts and image quality under stable low baseline HR. However, these studies only focused on patients with low HR. The specific effects

of HRV on imaging artifacts in the moderate HR range remain lacking systematic controlled verification. In addition, prospective electrocardiogram-triggered axial acquisition includes absolute phase and relative phase protocols. Few dedicated studies have clarified whether the two phase strategies exert targeted differential effects on coronary computed tomography angiography image quality, segment interpretability and lesion diagnostic performance in patients with sinus arrhythmia. Given the above clinical imaging dilemmas and research gaps, this study aimed to explore whether high HRV increases the incidence of coronary motion artifacts under moderate baseline HR. It also comparatively analyzed the influences of two prospective electrocardiogram-triggered axial protocols on image quality, segment evaluable rate and coronary lesion diagnostic accuracy in patients with sinus arrhythmia.

2. Materials and methods

This prospective observational cohort study was conducted with approval from the local institutional ethics review board. All participants provided written informed consent prior to enrollment.

2.1. Study Population

Between January 2022 and December 2024, consecutive patients with chest pain undergoing coronary computed tomography angiography (CCTA) were enrolled. Patients with moderate sinus arrhythmia were randomly allocated in a 1:1 ratio to receive scanning via either the absolute-phase acquisition protocol (Group B) or the relative-phase acquisition protocol (Group C). Propensity score matching[7] was subsequently performed at a 1:1 ratio, using age, sex and baseline HR as covariates. Patients with regular sinus rhythm enrolled during the same period were matched to serve as the control group (Group A). HRV (HRV) was defined as the difference between the maximum and minimum HRs recorded during CCTA[5].

2.2. Scan Protocol

All scans were acquired on a 256-slice, 16 cm wide-detector CT scanner (Revolution APEX, GE Healthcare, Waukesha, WI, USA) using prospective ECG-triggered axial mode. Tube voltage was tailored to each patient's body mass index. Patients were required to hold their breath and remain still during scanning. Auto gating and Smart Phase were used for automatic cardiac phase selection. Phase acquisition was adjusted by HR(bpm): $HR \leq 65$, 650–800 ms / 65%–80%; $65 < HR < 80$, 300–800 ms / 30%–80%; $HR \geq 80$, 350–500 ms / 35%–50%[8]. Images were reconstructed with True Fidelity deep learning reconstruction and second-generation SSF2 motion correction (GE Healthcare). No beta-blockers or nitroglycerin were given prior to examination.

A dual-head power injector (Stellant, Bayer) was used to inject 50 mL Omnipaque (350 mgI/mL, GE Healthcare) at 5 mL/s via the left or right antecubital vein, followed by a 30 mL saline flush at an identical injection rate.

2.3. Coronary Artery Segmentation and CCTA Image Quality Assessment

In accordance with the 2014 guidelines of the Society of Cardiovascular Computed Tomography (SCCT), the coronary arteries were divided into 18 segments[9]. The left main coronary artery (LM) was classified as part of the left anterior descending artery (LAD), and the ramus intermedius was categorized into the left circumflex artery (LCX).

Objective Image Quality Assessment

All measurements of attenuation and standard deviation (SD) were performed by an experienced physician at the aortic root level of the left main coronary artery. Regions of interest were placed at the maximal vascular area while carefully excluding vessel walls, calcified plaques, and non-calcified plaques. All parameters were measured in triplicate, and the mean value was calculated. Attenuation and SD of pericardial adipose tissue were simultaneously acquired (Fig. 1). Image noise, signal-to-noise ratio (SNR), and contrast-to-noise ratio (CNR) were quantitatively analyzed based on aortic root SD according to established criteria[9, 10]. SNR was defined as the mean aortic attenuation divided by corresponding SD. CNR was calculated as the attenuation difference between the vascular lumen and pericardial fat, normalized to the SD of pericardial fat attenuation.

Subjective Image Quality Assessment

Two experienced observers independently and blindly evaluated subjective image quality using the 18-segment coronary model. Discrepancies in scores were resolved by consensus reading. Image quality was graded using a four-point Likert scale[11]: 4, excellent (no artifacts); 3, good (minor artifacts, fully diagnostic); 2, acceptable (moderate artifacts, still interpretable); and 1, non-diagnostic (severe artifacts prohibiting evaluation), as shown in Fig. 1. Segments with a score ≥ 2 were considered eligible for diagnostic analysis. Segments with total occlusion, coronary stents, or diffuse severe calcification were excluded from evaluation.

2.4. Assessment of coronary artery stenosis by CCTA

All CCTA coronary segments were visually evaluated by two independent observers blinded to ICA data. Luminal stenosis was quantified as the percentage reduction of the vessel diameter in planes parallel and perpendicular to the vessel course. Discrepancies in reading were resolved by consensus. Stenosis grading adhered to the 2014 SCCT guidelines[9]. Segments with $\geq 50\%$ luminal stenosis were defined as positive. In vessels with multiple lesions, only the most severe stenosis was recorded. All coronary segments with a diameter ≥ 1.5 mm were included, while distal segments beyond occlusion were excluded. Segments with a score of 1 were consistent with significant stenosis ($\geq 50\%$ luminal narrowing).

2.5. Invasive Coronary Angiography

Intracoronary angiography (ICA) was conducted via the INNOVA 3100 system (GE Healthcare, Waukesha, Wisconsin) following standard protocols, with multiple angiographic views documented. Angiograms were independently evaluated in a blinded fashion by two readers masked to CCTA results. The definition of coronary segments, stenosis severity classification and assessment modalities remained consistent with the aforementioned criteria.

2.6.Statistical analysis

The Kolmogorov–Smirnov test was used to verify the normality of all variables. Continuous data with normal distribution were expressed as mean $\pm$ standard deviation, while non-normal data were presented as median and interquartile range. For comparisons among three or more groups, one-way ANOVA was used for normally distributed variables, and the Kruskal–Wallis test was applied for non-normally distributed variables. Categorical variables were compared using the chi-square test. Inter-observer agreement was assessed with the Kappa test.

The sensitivity, specificity, positive predictive value, negative predictive value, and diagnostic accuracy of CCTA in identifying obstructive coronary lesions ($\geq 50\%$ stenosis) were calculated on a per-segment, per-vessel, and per-patient basis, and analyzed using the Pearson chi-square test. With invasive coronary angiography served as the reference standard, non-diagnostic segments (score = 1) were included in the final analysis and classified as positive for luminal stenosis $\geq 50\%$. All statistical analyses were performed using SPSS 29.0. A two-tailed $P < 0.05$ was considered statistically significant.

3. Results

3.1. Baseline Clinical Characteristics of Enrolled Patients

A total of 100 patients were enrolled in each group, including 40 females and 60 males. The mean age was 54.81 ± 15.26 years, with a range from 24 to 90 years. There were no significant intergroup differences in gender distribution, age, height, body weight, body mass index (BMI), or mean HR among the three groups (all $P > 0.05$). The HRV (HRV) values of group A, group B and group C were 3.17 ± 1.39 bpm, 16.81 ± 8.37 bpm, and 16.44 ± 8.05 bpm, respectively. Compared with group A, both group B and group C presented significantly higher HRV (both $P < 0.05$), whereas no significant difference was observed between group B and group C ($P > 0.05$). Detailed data are summarized in Table 1.

Table 1
Patient Characteristics

	Group A, n = 100	Group B, n = 100	Group C, n = 100	P value
Coronary computed tomography angiography				
Age (years)	55.12 $\pm$ 14.84	54.81 $\pm$ 15.26	54.84 $\pm$ 15.30	0.995
Female (%)	40	40	40	1.000*
Height(cm)	167.73 $\pm$ 8.61	166.08 $\pm$ 8.16	165.80 $\pm$ 8.80	0.180
Weight(kg)	70.77 $\pm$ 14.20	68.89 $\pm$ 15.05	68.73 $\pm$ 12.91	0.329
BMI (kg/m2)	24.97 $\pm$ 3.52	24.79 $\pm$ 4.19	24.90 $\pm$ 3.32	0.671
HR	73.01 $\pm$ 10.74	74.13 $\pm$ 10.62	73.29 $\pm$ 11.18	0.750
HRV	3.17 $\pm$ 1.39#	16.81 $\pm$ 8.37	16.44 $\pm$ 8.05	0.000
NOTE: *=Chi-Square test, #Statistically different from Group A, BMI=Body Mass Index, HR = HR, HRV = HRV. Group A: regular sinus rhythm; Group B: sinus arrhythmia with absolute phase acquisition; Group C: sinus arrhythmia with relative phase acquisition.				

2.Image Quality Assessment

Objective image noise, signal-to-noise ratio (SNR), and contrast-to-noise ratio (CNR) were comparable across groups A, B, and C (all $P > 0.05$). The corresponding subjective image quality scores were 3.84 ± 0.61 , 3.76 ± 0.74 , and 3.62 ± 0.92 , with the highest in group A and the lowest in group C; overall intergroup differences were statistically significant (all $P < 0.001$). The rates of evaluable segments (score, 2–4 points) in the three groups were 96.44%, 94.89%, and 90.72%, and the rates of non-evaluable segments were 3.56%, 5.11%, and 9.28%, respectively. No difference in segment evaluability was found between group A and group B, whereas significant differences were detected between group A vs. group C and between group B vs. group C (both $P < 0.001$). See Fig. 2.

Further analysis showed that sinus arrhythmia-related non-diagnostic segments were markedly increased in Diagonal 1, Diagonal 2, left anterior descending artery distal, Left circumflex, distal, Obtuse marginal 1, especially with the relative phase acquisition protocol. Within diagnostic segments, image impairment (scores, 2–3 points) was most prominent in RCA2, also predominantly under the relative phase acquisition protocol. See Supplementary Table 1.

3. Diagnostic accuracy assessment

A total of 21 patients were consecutively enrolled in each of groups A, B, and C within one month. The patient-level, vessel-level, and segment-level diagnostic accuracies were 0.857, 0.873, and 0.931 in group A; 0.857, 0.889, and 0.958 in group B; and 0.810, 0.841, and 0.889 in group C. No significant intergroup differences were detected in patient-level and vessel-level diagnostic accuracy (all $P > 0.05$). In contrast, segment-level diagnostic accuracy differed significantly among the three groups ($P = 0.042$). Post hoc pairwise comparisons showed no significant difference between group A and group B ($P = 0.140$), whereas significant differences were noted between group A and group C ($P = 0.027$) and between group B and group C ($P = 0.004$) (Table 2).

Table 2
Diagnostic Accuracy Assessment

Parameter	Group	artifacts	TP	TN	FP	FN	Sensitivity (95% CI)	Specificity (95% CI)	PPV (95% CI)	NPV (95% CI)	Accuracy (%)
Per patient	Group A	0	15	3	1	2	0.882(0.657, 0.967)	0.750(0.301, 0.954)	0.938(0.698, 0.991)	0.600(0.231, 0.882)	0.857(0.645, 0.957)
	Group B	0	15	3	1	2	0.882(0.657, 0.967)	0.750(0.301, 0.954)	0.938(0.698, 0.991)	0.600(0.231, 0.882)	0.857(0.645, 0.957)
	Group C	1	15	2	2	2	0.882(0.657, 0.967)	0.500(0.150, 0.850)	0.882(0.657, 0.967)	0.500(0.150, 0.850)	0.810(0.590, 0.934)
	P-value						1.000	0.644	0.481	0.481	0.902
Per vessel	Group A	0	29	26	2	6	0.829(0.668, 0.923)	0.929(0.765, 0.982)	0.935(0.784, 0.985)	0.813(0.630, 0.921)	0.873(0.762, 0.939)
	Group B	3	30	26	4	3	0.909(0.747, 0.972)	0.867(0.690, 0.954)	0.882(0.720, 0.960)	0.897(0.723, 0.969)	0.889(0.781, 0.949)
	Group C	4	25	28	6	4	0.862(0.687, 0.951)	0.824(0.654, 0.922)	0.806(0.620, 0.917)	0.875(0.701, 0.959)	0.841(0.726, 0.916)
	P-value						0.416	0.729	0.395	0.672	0.785
Per segment	Group A	6	39	243	10	11	0.780(0.640, 0.878)	0.960(0.926, 0.979)	0.796(0.654, 0.890)	0.957(0.922, 0.977)	0.931(0.895, 0.955)
	Group B	7	42	251	8	5	0.894(0.764, 0.958)	0.969(0.939, 0.985)	0.840(0.703, 0.924)	0.980(0.953, 0.993)	0.958(0.928, 0.976)
	Group C	15	34	239	23	11	0.756(0.602, 0.864)	0.912(0.870, 0.943)	0.596(0.462, 0.717)	0.956(0.919, 0.977)	0.889(0.843, 0.924)
	P-value						0.237	0.186	0.002	0.315	0.042
NOTE: TP= True Positive; TN= True Negative; PPV= positive predictive value; NPV= negative predictive value, Artifacts are defined as a subjective score of 1.											

These results indicated that patients with moderate sinus arrhythmia had markedly increased coronary motion artifacts compared with patients with regular sinus rhythm (all $P < 0.001$). Among patients with sinus arrhythmia, the absolute phase acquisition protocol effectively reduced coronary motion artifacts and improved subjective image quality, imaging interpretability, and diagnostic accuracy compared with the relative phase acquisition protocol. Inter-observer agreement analysis revealed Kappa values of 0.937, 0.901, and 0.912 for subjective image quality evaluation, CCTA stenosis assessment, and ICA stenosis evaluation, respectively, indicating almost perfect inter-observer consistency and confirming the reliability of the present study data (Table 3).

Table 3
Consistency Analysis of Subjective Scores and Stenosis Rates

Subjective scoring(4/3/2/1)	Reader A	Reader B	Kappa Value
	3853/83/123/248	3841/89/110/267	0.937
Stenosis analysis			
CCTA (Positive/Negative)	136/773	122/787	0.901
ICA (Positive/Negative)	148/761	135/774	0.912

NOTE: CCTA=coronary computed tomography angiography; ICA=invasive coronary angiography

4. Discussion

The present findings demonstrated that high HRV significantly increased the risk of coronary motion artifacts in patients with a moderate HR. For individuals with sinus arrhythmia, the absolute phase acquisition protocol effectively reduced coronary motion artifacts, improved overall image quality and image interpretability, and further enhanced the diagnostic accuracy of CCTA.

Coronary motion artifacts are jointly induced by cardiac pulsation, pulmonary movement, and physical motion, resulting in coronary vascular blurring and positional dislocation [3]. A 16 cm wide-detector CT system was applied in this study to effectively avoid dislocation artifacts. All patients strictly complied with breath-holding instructions and maintained physical immobilization during scanning. Therefore, differences in coronary motion artifacts in this study were solely attributed to HR and HRV. The present results revealed that within the moderate HR range, patients with regular sinus rhythm exhibited significantly better subjective image quality than those with sinus arrhythmia, confirming that high HRV markedly increases the occurrence of coronary motion artifacts at this HR level.

Elevated HR and increased HRV collectively contribute to frequent coronary motion artifacts in patients with moderate HRs. The incidence of such artifacts is strongly associated with CCTA temporal resolution, with higher temporal resolution permitting scanning at higher HRs. Technical advances in dual-source CT have progressively improved HR tolerance: the first-generation system (0.33 s rotation) allows up to 49 beats/min [12], the second-generation model (0.28 s rotation) up to 60 beats/min [13], and the third-generation device (0.25 s rotation) up to 70 beats/min [14]. Although modern 256-slice CT provides better temporal resolution (140 ms) than conventional 64-slice CT (165 ms), motion artifacts remain common at HRs above 70 beats/min [15]. Fluctuating HRV interferes with optimal cardiac phase selection, rendering both mid-diastolic and end-systolic windows unstable for coronary imaging. Improper phase acquisition captures rapid coronary movement, and vessel displacement beyond temporal resolution compensation inevitably produces motion artifacts [3]. Overall, increased HR aggravates cardiac motion, whereas high HRV impairs phase matching; together, these factors degrade CCTA image quality in patients with moderate HRV. Consistent with previous studies, HRV has little influence on image quality at low HRs [5, 6]. This phenomenon may be explained by longer and more stable diastolic phases at low HRs, which reduce susceptibility to rhythmic fluctuations.

Patients with moderate HR and sinus arrhythmia are prone to frequent coronary motion artifacts, thereby reducing the subjective image quality of CCTA. Current routine clinical strategies for alleviating motion artifacts mainly include pre-examination intervention optimization, improvement of equipment temporal resolution, and application of motion correction reconstruction algorithms. Beyond these approaches, optimizing scanning acquisition modes serves as an effective supplementary measure. The present study confirmed that compared with the relative phase acquisition protocol, the absolute phase acquisition protocol can significantly reduce coronary motion artifacts and effectively improve subjective image quality.

Two mainstream prospective ECG-triggered axial acquisition protocols are widely used: absolute and relative temporal phase protocols. The absolute phase protocol is measured in milliseconds, with timing starting at the R-wave, and trigger onset adjusted according to HR. The relative phase protocol, by contrast, uses percentage units and determines acquisition onset via averaged pre-scan R-R intervals from ECG recordings. High HRV (HRV) causes significant R-R interval fluctuations throughout data acquisition, which complicates accurate diastolic window selection for the relative phase protocol. The absolute phase protocol, however, initiates timing strictly from the R-wave, making its acquisition unaffected by HRV variations. Therefore, the absolute phase protocol is optimal for patients with a regular moderate HR and elevated HRV, especially those with clinically intractable high HRV. It effectively reduces coronary motion artifacts, though its benefits for image interpretability and diagnostic accuracy require further clinical validation.

This study found the interpretable coronary segment rate was 94.89% in the absolute temporal phase group, lower than 96.44% in the regular sinus rhythm group but notably higher than 90.72% in the relative temporal phase group. The non-diagnostic segment rate was 5.11% in the absolute phase group, significantly lower than 9.28% in the relative phase group and marginally higher than 3.56% in the regular rhythm group, with all between-group differences statistically significant. Although sinus arrhythmia aggravates coronary motion artifacts and degrades overall image quality, the absolute temporal phase protocol is a reliable, optimal scanning strategy for patients with moderate HR and uncontrollable high HRV unresponsive to clinical management. Compared with the relative phase protocol, it effectively mitigates motion artifacts and improves subjective image quality and segment evaluability. Vorre et al. [16] documented a 100% evaluable coronary segment rate at a HR of 56 beats per minute, while the non-diagnostic rate increased to 10% at 74 beats per minute. A HR-stratified study by Miller et al. [17] using third-generation dual-source CT reported an overall diagnostic coronary segment rate of 91.3% across all HRs, with non-evaluable segments occupying 8.7%, and elevated HR confirmed as an independent risk factor for uninterpretable coronary segments. In the present study, with a mean HR of (74.13 ± 10.62) beats per minute, the absolute temporal phase protocol achieved a diagnostic segment rate of 94.89%, outperforming the 90% rate at 74 beats per minute and the 91.3% overall rate in prior research. These results confirm that the absolute phase protocol ensures high temporal positioning accuracy and satisfies scanning requirements for patients with moderate HR and high HRV. No significant intergroup differences in objective image quality scores were detected among the three groups, suggesting HR fluctuations and high HRV exerted no adverse impact on objective image quality. This outcome aligns with the conclusions of Schoepf et al. [18], further validating the stable and credible objective imaging baseline of this study.

Sinus arrhythmia significantly aggravates coronary motion artifacts and impairs overall subjective image quality. The rates of non-evaluable distal segments (Diagonal 1, Diagonal 2, left anterior descending artery distal, Left circumflex, distal, Obtuse marginal 1) were markedly higher in the arrhythmia group, particularly in the relative phase acquisition subgroup. These problematic segments were thin, with vessel diameters generally below 1.5 mm and mainly distributed in the terminal coronary microbranches. Clinically, distal branch microcirculation lesions can be well controlled and followed up with standardized pharmacotherapy[7]. Though increased non-diagnostic distal segments slightly decreased overall image quality scores, they had minimal influence on the core diagnostic efficiency for coronary artery disease. Stratified analysis showed that diagnostic accuracy of the relative phase protocol was significantly lower than that of the absolute phase protocol and the normal sinus rhythm group only at the segmental level. No intergroup differences were found in per-patient and per-vessel diagnostic accuracy. This pattern conforms to the typical distribution of coronary atherosclerotic lesions: high-risk plaques and severe stenosis primarily occur in large proximal and middle coronary segments, while distal microbranches have low plaque burden and less pathological involvement[19]. Previous studies using identical imaging equipment support our findings. Liang et al.[20] reported per-patient, per-vessel and per-segment CCTA diagnostic accuracies of 95.3%, 94.9% and 95.3%, and Xu et al.[21] recorded a single-segment accuracy of 91.2%. For dual-source CT, historical data showed a single-segment accuracy of 91.9% and a per-patient accuracy of 95.0%[22]. A large 320-slit CT cohort study (1023 cases) revealed a per-patient accuracy of only 89%[23]. Notably, our adopted absolute phase fixed acquisition protocol achieved a segmental diagnostic accuracy of 95.8%, demonstrating better diagnostic performance than conventional acquisition regimens in current mainstream research.

Several limitations exist in this study. First, all images were collected from a single center using a GE Healthcare 256-slice 16 cm wide-detector CT with second-generation dedicated motion correction reconstruction. Constrained by hardware configuration, tube parameters and proprietary iterative algorithms, the results cannot be directly generalized to CT devices of other brands or specifications. Cross-device and cross-algorithm applicability requires further prospective verification. Second, this study only included patients with sinus arrhythmia at moderate HRs to compare two ECG-triggered acquisition protocols. Subjects with arrhythmia at low or high HRs were excluded, and the efficacy of the two phase strategies under different HRloads remains to be further explored. Third, this was a single-center retrospective study. Despite the adoption of ICA as the gold standard and reliable baseline data, inevitable selection bias limited its generalizability. Large-sample, multicenter prospective studies are needed to improve external validity and confirm the clinical value of the absolute phase acquisition protocol.

In conclusion, moderate HR with elevated HRV markedly increases coronary motion artifacts and degrades CCTA image quality. Compared with the conventional relative phase protocol, the absolute phase acquisition effectively alleviates HRV-related rhythmic interference, reduces motion artifacts, and improves segment evaluability and diagnostic accuracy. For patients with moderate HR and uncontrollable high HRV, the absolute phase protocol is recommended to optimize imaging quality and ensure robust coronary assessment performance.

Declarations

Reporting Checklist

The authors have completed the STROBE reporting checklist.

Conflicts of Interest:

All authors have completed the ICMJE uniform disclosure form. All authors have no conflicts of interest to declare.

Ethical Statement

The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the ethics committee of Affiliated BenQ Hospital of Nanjing Medical University (No. 2022-KL002) and all subjects provided written informed consent before participating in the study.

Author Contribution

W.N.Q designed the study and wrote the paper. J.J.Z. and Y.X.Z. analyzed the CCTA Image Quality. Y.H.F. and L.G. performed an independent blinded assessment of the presence of lung motion on CCTA images. J.L. and H.B.M. assessed the Invasive Coronary Angiography. H.B.M. were responsible for the study design, and the final approval of the version to be published. All authors read and approved the final manuscript.

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Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

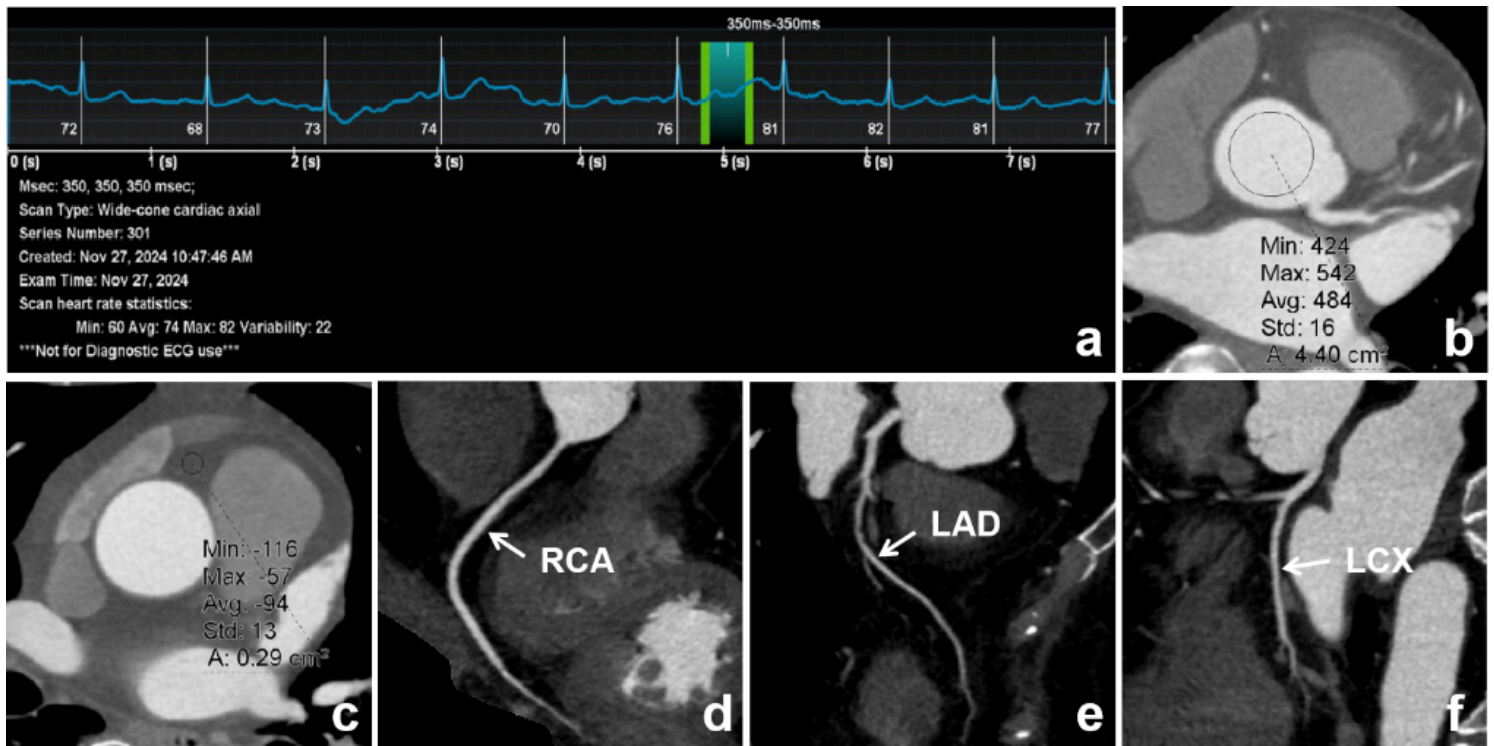


Figure 1

A 60-year-old woman. The mean HR recorded during coronary CTA was 74 bpm, with a HRV (HRV) of 22 bpm (Fig a). At the level of the left main coronary artery, the mean attenuation of the ascending aortic root was 484 HU, with a standard deviation of 16 HU (Fig b). The mean CT attenuation of the pericardial fat was measured at -93 HU, with a standard deviation of 11 HU (Fig c). Curved planar reconstructions of the right coronary artery (Fig d), left anterior descending artery (Fig e), and left circumflex artery (Fig f) demonstrated clear vessel margins, with an image quality score of 4.

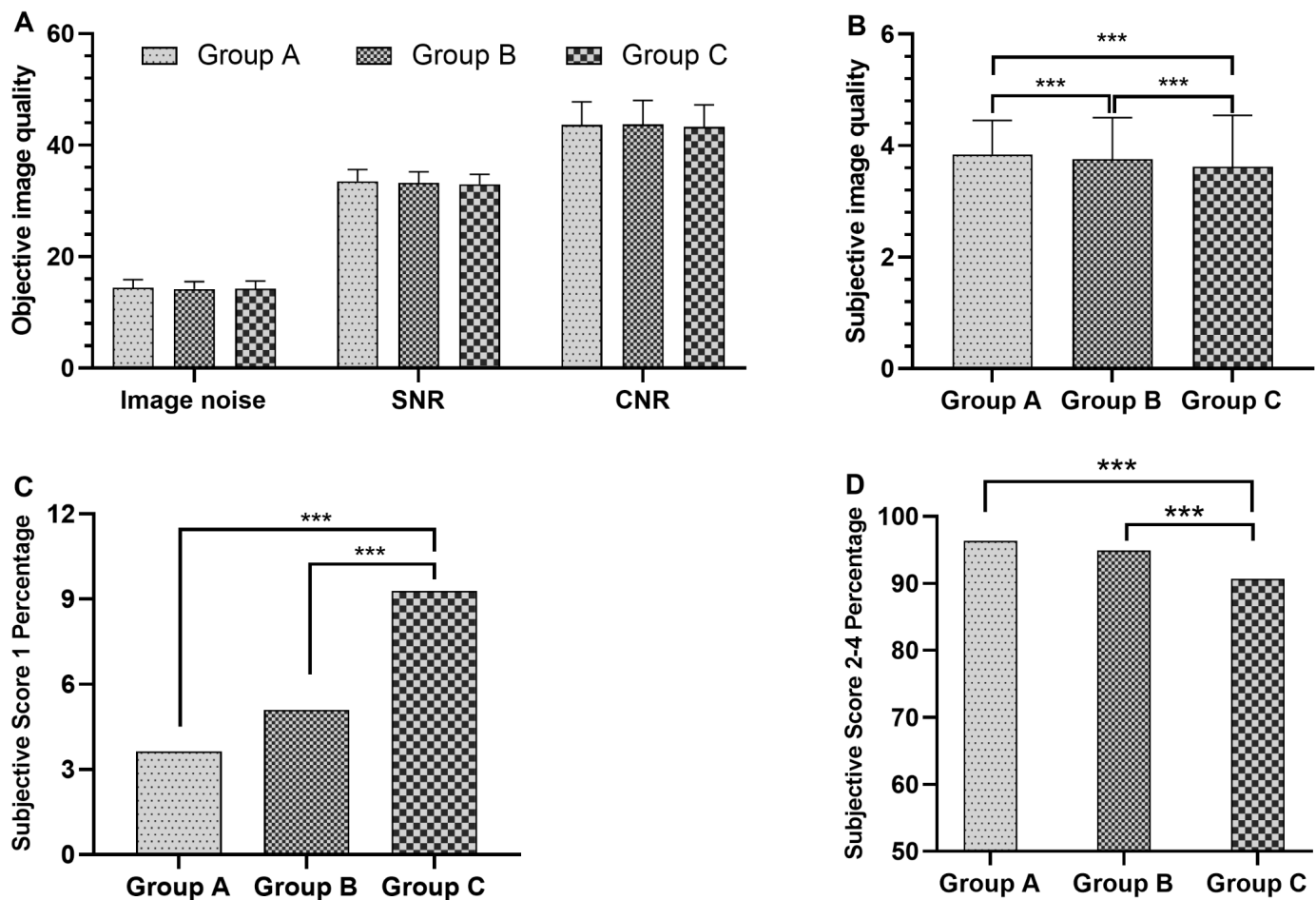


Figure 2

Image Quality Assessment. No significant differences in image noise, signal-to-noise ratio, or contrast-to-noise ratio were observed among groups A, B, and C (all $P > 0.05$) (Figure A). The subjective image quality score was the highest in group A and the lowest in group C, with a significant intergroup difference ($*** < 0.001$) (Figure B). The proportion of non-diagnostic coronary segments (subjective score = 1) was the lowest in group A and the highest in group C; no significant difference was found between group A and group B, whereas significant differences were detected between group A and group C, as well as between group B and group C (both $P < 0.001$) (Figure C). The proportion of evaluable coronary segments (subjective scores 2–4) was the highest in group A and the lowest in group C; similarly, there was no significant difference between group A and group B, while pairwise comparisons of group A versus group C and group B versus group C showed significant differences (both $P < 0.001$) (Figure D). Group A: regular sinus rhythm; Group B: sinus arrhythmia with absolute phase acquisition; Group C: sinus arrhythmia with relative phase acquisition.