

Optimization of Personalized Contrast Agent Injection Protocols Based on High Heart Rate: A Study Aimed at Enhancing Coronary CTA Image Quality

Lishu Zhu

First Affiliated Hospital of Chongqing Medical University

Weiye Liang

First Affiliated Hospital of Chongqing Medical University

Wei Ren

CT Imaging Research Center, GE Healthcare China

Peng Gang

pg24k311@sina.com

First Affiliated Hospital of Chongqing Medical University

Zhiwei Zhang

First Affiliated Hospital of Chongqing Medical University

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Abstract

Objective

Using wide-detector CT (WDCT), this study examines the effect of integrating heart rate into a P3T-based personalized contrast agent injection protocol on CCTA image quality in patients with high heart rates ($HR \geq 90$ bpm), and further validates the clinical efficacy of the modified protocol.

Methods

This retrospective study included 160 patients who underwent WDCT coronary CTA from January to July 2024. Patients were divided into a low-HR group (heart rate < 90 bpm, $n = 79$) and a high-HR group (heart rate ≥ 90 bpm, $n = 81$). Image reconstruction utilized the SSF2 motion-correction algorithm after prospective ECG-gated acquisition. The contrast protocol was based on the P3T technique, considering the patient's BMI and tube voltage. Coronary image quality was evaluated through objective metrics (luminal attenuation, CNR, SNR) and a 5-point Likert scale. In an independent validation cohort (August–December 2024; $n = 80$; $HR \geq 90$ bpm), the injection rate and volume for patients with a high heart rate were proportionally adjusted based on the reduction in CT attenuation to validate the effectiveness of the modified protocol.

Result

In the Primary Cohort, the conventional P3T protocol led to a 9.7%–16.3% reduction in coronary CT attenuation in the high-HR group compared to the low-HR group, along with significant decreases in CNR and SNR. After implementing the modified protocol in the validation cohort, CT attenuation and CNR for all coronary branches matched those of the low-HR group (all $P > 0.05$) and were significantly better than the conventional high-HR group (all $P < 0.01$). No significant differences were found in SVC or RA CT attenuation or CNR among the groups ($P > 0.05$), with no new venous artefacts detected. Subjective image quality was rated diagnostic (scores 4–5) across all groups, with no significant differences ($P > 0.05$) and excellent interobserver agreement ($ICC > 0.80$).

Conclusion

Using wide-detector CT and the SSF2 motion-correction algorithm, the heart-rate–integrated P3T personalized injection protocol improves coronary opacification and diagnostic confidence in high-heart-rate patients, without increasing artefacts in the superior vena cava or right atrium. This facilitates broader use of CCTA in these populations.

Introduction

Coronary CT angiography (CCTA) is a noninvasive way to assess coronary artery disease and is highly sensitive and accurate for detecting CAD[1, 2]. If the patient's heart rate is high, the rhythm is irregular, or they cannot hold their breath well during CCTA, motion artifacts may occur and make it harder to evaluate lesions accurately[3].

Wide-detector computed tomography (WDCT), with its 16-cm detector coverage, enables true whole-heart volumetric acquisition, enhancing temporal resolution in the z-axis and reducing overall scan time. When integrated with the SnapShot Freeze 2 (SSF2) motion-correction algorithm, WDCT effectively mitigates misregistration artifacts arising from heart rate fluctuations and arrhythmias, thereby improving visualization of coronary artery trunks and branches[4–6]. Remarkably, it can yield diagnostic-quality images even when patients are breathing freely[7, 8].

Optimization of contrast injection protocols has remained a longstanding area of focus in CT clinical practice[9–11]. For CCTA, the ideal arterial enhancement is 325HU-500HU[12, 13]. Suboptimal enhancement (< 325 HU) diminishes confidence in stenosis assessment[14–16], whereas excessive enhancement (> 500 HU) can introduce beam-hardening artifacts and partial-volume effects[17, 18]. Personalized contrast injection protocols are advocated to achieve precise control of contrast volume; nevertheless, contemporary injector systems predominantly rely on body weight, contrast concentration, and tube voltage to generate individualized plans, largely overlooking the potential impact of heart rate on coronary arterial enhancement[19, 20]. However, in patients with elevated heart rates, reduced stroke volume limits the amount of blood ejected per beat, thereby delivering a smaller contrast bolus to the target coronary vessels. The higher blood-flow velocity associated with high heart rates also produces stronger “washout” and “dilution” effects on intraluminal contrast, making the peak concentration difficult to maintain and causing it to fall rapidly, which may affect coronary enhancement[21, 22].

In this study, wide-detector CT integrated with a motion-correction algorithm was utilized, together with the conventional weight-dependent protocol (P3T Cardiac™), to compare the impact of normal versus elevated heart rates on CCTA image quality. Based on the objective results, we adjusted the injection protocol for patients with high heart rates, developed a modified personalized contrast protocol suited for them, and then assessed how effective this improved protocol is in clinical practice.

Materials and Methods

This retrospective study was approved by the Ethics Committee of the First Affiliated Hospital of Chongqing Medical University, Chongqing, China (Ethics No. 2025-432-01), with a waiver of informed consent.

Study Patients

From January to July 2024, we included 166 patients who underwent wide-detector CT CCTA at our hospital. All of them received the standard P3T contrast protocol. Exclusion criteria were: severe motion artefacts; extensive coronary artery calcification with severe beam-hardening artefacts; severe streak

artefacts in the right coronary artery due to implanted devices; known allergy to iodine-based contrast media; or renal insufficiency. Among the 181 patients initially screened, 8 were excluded because they underwent combined vascular studies, 3 due to severe vascular artefacts, 5 because of heavy calcification, 2 because of pacemakers, and 3 because of coronary stents. A total of 160 patients were finally included. They were grouped according to heart rate: 79 in the low-heart-rate group (< 90 bpm) and 81 in the high-heart-rate group ($\geq$ 90 bpm) (Fig. 1).

CT Acquisition and image processing

All patients underwent prospective ECG-gated volumetric scanning with a 256-slice wide-detector CT scanner (Revolution CT, GE Healthcare). The scanning protocol consisted of localization, calcium scoring, bolus tracking, and coronary CTA acquisition. A low-dose axial scan was first performed to define the scan range and to calculate the coronary calcium score. The region of interest for bolus tracking was placed in the descending aorta, 2 cm below the tracheal bifurcation, with a trigger threshold of 100 HU. Scanning was initiated 6 seconds after reaching the threshold. Tube current was automatically adjusted with a noise index of 22; tube voltage was set at 100 kV; gantry rotation time was 0.28 s. A 160-mm detector was used for prospective volumetric acquisition, with image reconstruction performed at 70%–80% and 40%–60% of the R–R interval.

After image acquisition, axial datasets were reconstructed using a 50% Adaptive Statistical Iterative Reconstruction-V (ASiR-V, GE Healthcare) algorithm[23, 24], with a slice thickness of 0.625 mm and an interval of 0.625 mm. The optimal cardiac phase for SSF2 motion correction was automatically identified using the Smart Phase based on heart rate. The processed images were then transferred to the AW 4.7 (Advantage Workstation 4.7) workstation for Volume Rendering (VR) and Curved Planar Reconstruction (CPR).

Contrast agent injection protocol

Contrast medium was administered using a dual-chamber high-pressure injector (Stellant, MEDRAD, Bayer Healthcare). The contrast agent used was iopromide (Ultravist, 370 mg/mL; Bayer Healthcare). The P3T Cardiac system automatically calculates the contrast medium dose and injection rate based on tube voltage and patient BMI. The injection duration was 11 seconds. The standard protocol included a 40 mL saline chaser, a maximum injection rate of 5 mL/s, and an iodine load ranging from 16 g to 31 g. Additional settings included a 10-second duration adjustment, a minimum injection time of 10 seconds, a cutoff adjustment of 3 seconds, a scan duration of 1 second, and a maximum pressure limit of 325 psi. The weight factor was determined according to the patient's body weight (Table 1). This constituted the traditional P3T protocol.

Table 1
Setting of body weight factors under different body weights

Body weight interval(kg)	<39	39–59	60–74	75–94	95–109	110–125	>125
Body weight factor(gl/kg)	0.405	0.405	0.324	0.304	0.284	0.251	0.243

Image analysis

Objective evaluation: Quantitative measurements were performed on an AW 4.7 workstation. Regions of interest (ROIs) were placed in the pectoralis major muscle, aortic root (AO), mid-segments of the left anterior descending (LAD), left circumflex (LCX), and right coronary artery (RCA), as well as the superior vena cava (SVC) and right atrium (RA). Each measurement was repeated three times and averaged. The contrast-to-noise ratio (CNR) was calculated as: $CNR = (\text{vascular attenuation} - \text{muscle attenuation}) / \text{muscle SD}$.

Subjective evaluation: Two senior radiologists independently reviewed the images, blinded to the study protocol and reconstruction method. The image order was randomized. Window settings were adjusted as needed. Image quality was graded on a 5-point Likert scale[25]: 1 = non-diagnostic (severe artifacts preventing coronary assessment); 2 = suboptimal but interpretable (artifacts secondary to coronary motion); 3 = acceptable (adequate quality despite moderate artifacts); 4 = good (minor motion artifacts only); 5 = excellent (minimal or no artifacts with clear vessel wall delineation, fully suitable for diagnosis). Discrepancies were resolved by consensus.

Validation Cohort

From August to December 2024, an independent validation cohort was consecutively recruited from the same institution for this retrospective study. Their contrast injection protocol was improved by proportionally adjusting the injection rate and total volume based on the traditional P3T method, using the CT attenuation difference between high-HR and low-HR patients from the initial study as a reference, while maintaining the same injection duration. All patients had heart rates ≥ 90 bpm and followed the same exclusion criteria, imaging process, and analysis methods as the primary cohort (Fig. 1). A total of 80 patients were included in the study.

Statistical analysis

All statistical analyses were conducted using R (version 4.3.2) and Python (version 3.12). Continuous variables were tested for normality using the Shapiro–Wilk test. Normally distributed variables were presented as mean $\pm$ standard deviation (SD), and compared using one-way analysis of variance (ANOVA) or analysis of covariance (ANCOVA) with adjustment for body mass index (BMI) and tube voltage (kVp) when appropriate. Non-normally distributed variables were presented as median and interquartile range (IQR), and compared using the Kruskal–Wallis H test. For objective image quality, luminal attenuation (HU), contrast-to-noise ratio (CNR), and signal-to-noise ratio (SNR) were compared among the three groups (low HR < 90 bpm, high HR ≥ 90 bpm, and improved high HR ≥ 90 bpm).

Estimated marginal means (EMMeans) with 95% confidence intervals (CIs) were calculated based on ANCOVA for luminal attenuation. Subjective image quality was assessed using a 5-point Likert scale (1 = non-diagnostic, 5 = excellent). Inter-observer agreement between the two radiologists was evaluated using the intraclass correlation coefficient (ICC, two-way random effects model). Differences in Likert scores among groups were tested using the Kruskal–Wallis test. All statistical tests were two-sided, and P values < 0.05 was considered statistically significant.

Results

Baseline characteristics

Table 2 provides a summary of baseline demographic and clinical characteristics for the study population. The primary cohort—comprising the low-HR group (< 90 bpm) and high-HR group (≥ 90 bpm)—and the validation cohort (≥ 90 bpm) demonstrated no statistically significant differences across baseline parameters, such as age, sex, height, weight, body mass index (BMI), and heart rate (all P > 0.05).

Table 2
Baseline demographic and clinical characteristics of the study population.

Parameter	Primary Cohort		Validation Cohort	P-value
	Low HR(< 90 bpm)	High HR(≥ 90 bpm)	(≥ 90 bpm)	
Number	79	81	80	
Male sex, n (%)	36(45.57)	43(53.09)	38(47.5)	0.61
Age (years)	61.9 ± 13.0	58.3 ± 14.0	58.3 ± 10.9	0.29
Height (m)	1.6 ± 0.1	1.7 ± 0.1	1.6 ± 0.1	0.34
Body Weight (kg)	64.2 ± 12.3	67.2 ± 11.1	61.4 ± 10.2	0.42
Body Mass Index (kg/cm2)	24.0 ± 3.8	24.3 ± 3.0	23.5 ± 3.2	0.17
Heart Rate (bpm)	71.4 ± 12.0	103.2 ± 12.5	99.2 ± 11.9	0.06

Objective image quality

Quantitative image quality metrics, including luminal attenuation (HU), contrast-to-noise ratio (CNR), and signal-to-noise ratio (SNR), for the aortic root (AO) and major coronary branches (LAD, LCX, RCA) are summarised in Table 3. Analysis of the Primary Cohort revealed that once heart rate exceeded 90 bpm, CT attenuation across all coronary branches declined markedly by approximately 9.7%–16.3% relative to the low-HR cohort. Consequently, the validation cohort received a proportional increase in contrast injection parameters, achieved by increasing both the injection flow rate and total volume by 10% over

the traditional P3T protocol, while maintaining the same injection duration. The results showed that the three groups differed significantly in average CT attenuation, CNR, and SNR (all $P < 0.01$). Pairwise analysis revealed that the Validation Cohort exhibited attenuation and CNR levels comparable to those of the low-HR group in the Primary Cohort (both $P > 0.05$). Both were significantly higher than those of the traditional high-HR group (both $P < 0.01$).

Notably, CT attenuation in the LAD, LCX, and RCA declined as heart rate increased, whereas no significant differences were detected in the SVC or RA (all $P > 0.05$). Estimated marginal means (EMMeans) of luminal attenuation, adjusted by ANCOVA, are displayed in Fig. 1, while the distributions of CNR and SNR across groups are depicted in Figs. 2 and 3, respectively.

Table 3
Objective image quality parameters across the three groups (HU, CNR, SNR).

Anatomical structure		Primary Cohort		Validation Cohort (≥ 90 bpm) 3	P_FDR(BH)	P(1 vs 2)	P(1 vs 3)	P(2 vs 3)
		Low HR (< 90 bpm) 1	High HR (≥ 90 bpm) 2					
CT value	AO	423.84 $\pm$ 67.42	357.98 $\pm$ 90.38	402.51 $\pm$ 62.15	<0.001	<0.001	0.037	0.002
	LAD	356.09 $\pm$ 73.32	302.86 $\pm$ 73.95	341.29 $\pm$ 53.97	<0.001	<0.001	0.185	0.003
	LCX	344.7 $\pm$ 63.02	295.4 $\pm$ 72.0	344.05 $\pm$ 54.06	<0.001	<0.001	0.718	<0.001
	RCA	370.24 $\pm$ 70.87	318.45 $\pm$ 82.53	356.98 $\pm$ 60.28	<0.001	<0.001	0.476	0.002
CNR value	AO	15.26 $\pm$ 2.79	12.73 $\pm$ 3.04	13.8 $\pm$ 2.77	<0.001	<0.001	0.004	0.0496
	LAD	7.35 $\pm$ 1.7	6.22 $\pm$ 1.61	7.28 $\pm$ 0.94	<0.001	<0.001	0.944	<0.001
	LCX	7.15 $\pm$ 1.51	6.26 $\pm$ 1.56	7.59 $\pm$ 1.22	<0.001	<0.001	0.131	<0.001
	RCA	7.9 $\pm$ 1.76	6.67 $\pm$ 1.74	7.79 $\pm$ 1.52	<0.001	<0.001	0.903	<0.001
SNR value	AO	17.81 $\pm$ 2.93	15.47 $\pm$ 3.08	16.26 $\pm$ 3.1	<0.001	<0.001	0.004	0.226
	LAD	8.86 $\pm$ 1.69	7.83 $\pm$ 1.56	8.87 $\pm$ 1.02	<0.001	<0.001	1.000	<0.001
	LCX	8.67 $\pm$ 1.5	7.86 $\pm$ 1.51	9.22 $\pm$ 1.34	<0.001	0.002	0.046	<0.001
	RCA	9.44 $\pm$ 1.75	8.3 $\pm$ 1.67	9.38 $\pm$ 1.59	<0.001	<0.001	0.973	<0.001
Note: AO=aortic root, LAD=left anterior descending branch, LCX=left spiral branch, RCA=right coronary artery, CT value=Computed Tomography Value, CNR=contrast-to-noise ratio,SNR=Signal-to-Noise Ratio. P < 0.05 indicated statistically significant difference.All P values were adjusted for multiple testing using the Benjamini–Hochberg procedure. All significant results remained after FDR correction.								

Subjective image quality

Subjective image quality was evaluated using a 5-point Likert scale (1 = non-diagnostic, 5 = excellent) in Table 4. Median Likert scores for the LAD, LCX, and RCA ranged from 4.0 to 5.0 across all groups, confirming diagnostic image quality in all cases. No significant intergroup differences were observed (all P > 0.05). Inter-observer agreement between the two radiologists was excellent (ICC > 0.80).

Figure 4 presents representative curved planar reformatted (CPR) images from each study group, demonstrating that the Validation Cohort, applying the modified P3T protocol, attained CT attenuation values equivalent to those of the low–heart–rate subgroup within the Primary Cohort, along with a substantial reduction in motion artefacts.

Table 4
Subjective image quality (Likert scores) of coronary branches.

Anatomical structure	Primary Cohort		Validation Cohort HR (≥ 90 bpm)	P-value	H-value	ICC (2,1)
	Low HR (< 90 bpm)	High HR (≥ 90 bpm)				
LAD	4.5 (4.0–4.5)	4.5 (4.0–4.5)	4.5 (4.0–4.5)	0.367	2	-0.89
LCX	4.0 (4.0–4.5)	4.0 (4.0–4.5)	4.0 (4.0–4.5)	0.977	0.05	-0.89
RCA	4.5 (4.0–5.0)	4.5 (4.0–5.0)	4.5 (4.0–5.0)	0.67	0.8	-0.85
Note: LAD=left anterior descending branch, LCX=left spiral branch, RCA=right coronary artery. P < 0.05 indicated statistically significant difference.						

Discussion

Achieving diagnostic-quality CCTA images in patients with high heart rates remains a challenge. The advent of wide-detector CT scanners has significantly enhanced temporal resolution, and when combined with motion correction algorithms [26, 27], has effectively resolved motion-related artefacts in patients with elevated heart rates [28–31]. However, the effect of contrast agent protocols on CT attenuation and image quality when the heart rate is high warrants greater attention.

Previous studies have indicated a clinical diagnostic threshold of 325 HU for CCTA[13]. In our Primary Cohort, using the traditional weight-based P3T protocol, we found that patients with heart rates above 90 bpm often failed to achieve adequate vascular enhancement (> 325 HU). Many studies did not address the insufficient coronary CT attenuation observed at high heart rates, likely because of the contrast administration protocols used. Fixed protocols or weight-based empirical dosing often deliver more contrast, such as determining dose by patient weight or fixed parameters (e.g., 50 mL at 5 mL/s)[32–34]. These high CT values can mask the effect of heart rate; therefore, simple protocols may cause overly high contrast in the SVC or RA, leading to increased CT attenuation and beam-hardening artefacts. Evidence demonstrates that cardiac output—rather than BMI—is the predominant determinant of arterial contrast enhancement[35], underscoring the hemodynamic influence of heart rate.

In this study, contrast dosing was individualised according to tube voltage and BMI, thereby reducing the overall iodine burden. Beyond these parameters, heart rate was incorporated as an additional determinant. In the Primary Cohort, we found that when HR exceeded 90 bpm, CT attenuation decreased

by 9.7%–16.3% compared with patients with lower HR. Based on this result, we chose 10% as the minimum adjustment and proportionally modified the P3T injection protocol. Specifically, for HR > 90 bpm, the injection rate and contrast volume were each increased by 10%, with the injection duration kept constant. This adjustment compensated for the reduction in stroke volume and cardiac output associated with tachycardia[21, 22]. A higher flow rate reduces the dilution effect, ensures stable vascular enhancement, and prevents excessive opacification in the RA and SVC. Our goal was to create a heart-rate–adaptive contrast strategy to improve coronary enhancement and overall CCTA quality in patients whose HR exceeds 90 bpm.

In the Primary Cohort, applying the conventional P3T contrast protocol and performing quantitative assessment revealed that the aortic and coronary (LAD, LCX, RCA) CT attenuation, CNR, and SNR in the high-heart-rate subgroup were markedly reduced compared with the low-heart-rate subgroup, falling below the clinical diagnostic threshold of 325 HU for CCTA. This phenomenon is likely attributable to tachycardia-induced shortening of the cardiac cycle, particularly the diastolic phase. Because coronary blood flow is more stable during diastole and contrast filling is more complete, a shorter diastolic period results in reduced contrast filling time, leading to lower intravascular contrast concentration. Elevated heart rates intensify cardiac motion and hemodynamic fluctuations, potentially compromising homogeneous contrast distribution and resulting in heterogeneous vascular opacification, which can lead to diminished diagnostic confidence. Despite the capability of wide-detector CT combined with single-heartbeat acquisition and SSF2 reconstruction to mitigate motion artefacts[5], inadequate vascular enhancement (< 300 HU) still compromises stenosis detection accuracy, particularly in distal coronary segments[15]. These findings further substantiate that inadequate contrast enhancement is the predominant contributor to image quality degradation in patients with elevated heart rates. The Primary Cohort findings reinforced our rationale and confidence in implementing a heart-rate–adaptive modification to the P3T injection protocol. The degree of CT attenuation reduction observed in the high-heart-rate subgroup relative to the low-heart-rate subgroup offered quantitative direction for developing a refined implementation strategy.

Based on findings from the Primary Cohort, we revised the conventional P3T contrast injection protocol by increasing the injection rate by 10% and proportionally increasing the contrast volume, while maintaining a constant injection duration. A corresponding Validation Cohort was assembled to assess the effectiveness of this modified protocol. The Validation Cohort demonstrated that using the improved P3T protocol with wide-detector CT clearly enhances the visualisation of coronary arteries in patients with high heart rates. Quantitative assessments indicated that CT attenuation and CNR for the LAD, LCX, and RCA in the Validation Cohort were equivalent to those of the Primary Cohort’s low-HR subgroup (all $P > 0.05$), and substantially higher than those observed in the high-HR subgroup. No significant differences in SVC and RA CT attenuation or CNR were observed across the three groups, indicating that the higher injection rate did not lead to venous contamination or artefacts. Subjective image quality scores for LAD, LCX, and RCA were comparable among all groups (all $P > 0.05$). Collectively, the findings demonstrate that proportional adjustment of the P3T protocol according to target CT attenuation, using a minimum increment of approximately 10%, is sufficient to achieve optimal enhancement. This

modification enabled the Validation Cohort to obtain coronary opacification comparable to that of the Primary Cohort's low-heart rate subgroup under the conventional P3T protocol. In contrast, the higher injection rate and contrast volume did not induce SVC contrast pooling or additional artefacts. Thus, a 10% increment appears to represent an effective threshold for enhancement. Moreover, the Validation Cohort also demonstrated high diagnostic image quality, even at high HR, indicating that the strategy is clinically feasible. This finding further supports that high-rate contrast injection can improve vascular CT attenuation [36]. The underlying mechanism may be that faster injection raises iodine concentration and delivery, which helps counteract the dilution caused by reduced cardiac output in high-HR patients.

In the present study, subjective image-quality scores did not differ significantly among the three groups, aligning with findings from earlier investigations. Phantom experiments[37] also demonstrated that diagnostic-quality images can still be achieved even when heart rates reach 100 beats per minute (bpm). Similarly, Andreini et al. [33] reported that patients with higher heart rates (> 80 bpm) exhibited mean Likert scores (3.35 ± 1.3 on a four-point scale) comparable to those with lower heart rates (< 65 bpm; 3.39 ± 1.3). The high performance of the SSF2 algorithm enables CCTA to be performed in patients who were previously considered unsuitable due to arrhythmia or limited breath-holding capacity, thereby reducing examination failure rates. Multiple studies have confirmed the diagnostic performance of the SSF2 algorithm[5, 38]. In addition, wide-detector CT—featuring an effective temporal resolution of 29 ms and single-heartbeat acquisition (< 1 s)—together with free-breathing capability[39, 40], markedly reduces motion artefacts, improves scan tolerance in patients with elevated heart rates[5, 40, 41], and significantly enhances subjective image quality. Our results regarding the clinical utility of SSF2 are in agreement with prior research. However, because Likert scoring focuses on continuity and artefacts, low arterial enhancement (< 325 HU) can lower confidence and accuracy in detecting stenosis[14–16]. Thus, attaining the required diagnostic enhancement threshold is essential in patients with high HR.

This study investigated the causes of suboptimal CCTA image quality in patients with elevated heart rates and identified that hemodynamic alterations compromise vascular contrast enhancement. Accordingly, heart rate should be incorporated as a key parameter in tailoring contrast injection strategies. We proposed a novel contrast protocol for high-heart-rate patients that integrates advanced CT scanner technology, state-of-the-art motion correction algorithms, and heart rate modulation to mitigate the contrast dilution effect induced by tachycardia effectively. The optimised contrast protocol substantially reduced the need for repeat scans, enhanced diagnostic confidence to a level comparable with that of low-heart-rate patients, and successfully broadened the clinical applicability of CCTA to challenging populations, including those with elevated heart rates and special diagnostic requirements. This study has several limitations. First, it was a single-centre study with a relatively small sample size. Larger, multicenter investigations will be required to validate and further substantiate the value and potential clinical application of wide-detector CT, coupled with the modified contrast-injection strategy, in CCTA examinations. Second, patients with heart failure or severe valvular disease were excluded, and the distinct hemodynamic profiles of these populations may limit the generalizability of the proposed protocol. Third, all imaging data were acquired using a 256-slice MDCT system from a single

manufacturer, which limits the ability to compare our findings with results from scanners produced by other vendors.

In conclusion, combining wide-detector CT and SSF2 motion correction, and incorporating heart-rate modulation into the P3T individualised contrast-injection protocol substantially improves image quality in patients with elevated heart rates, achieving diagnostic performance comparable to that of low-HR patients while avoiding additional streak artefacts in the superior vena cava and right atrium. This optimised strategy has the potential to reduce repeat examinations and enhance diagnostic confidence for small coronary lesions, thereby promoting wider adoption of CCTA in patients with high heart rates.

Declarations

Ethics approval statement

This retrospective study was approved by the Ethics Committee of the First Affiliated Hospital of Chongqing Medical University, Chongqing, China (Ethics No. 2025-432-01), with a waiver of informed consent, and the study was performed in accordance with the Declaration of Helsinki of the World Medical Association.

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Data availability statement

The raw data that support the findings of this study are available from the corresponding author, upon reasonable request.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

Guarantors of integrity of entire study, Lishu Zhu, Weiyi Jiang, Zhiwei Zhang,Gang Peng; study design and data acquisition, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; approval of final version of submitted manuscript, all authors; agrees to ensure any questions related to the work are appropriately resolved, all authors; literature research, Weiyi Jiang;

clinical studies, Lishu Zhu, Wei Ren, Zhiwei Zhang, Gang Peng; statistical analysis, Lishu Zhu,; and manuscript editing, Lishu Zhu, Zhiwei Zhang, Gang Peng.

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Figures

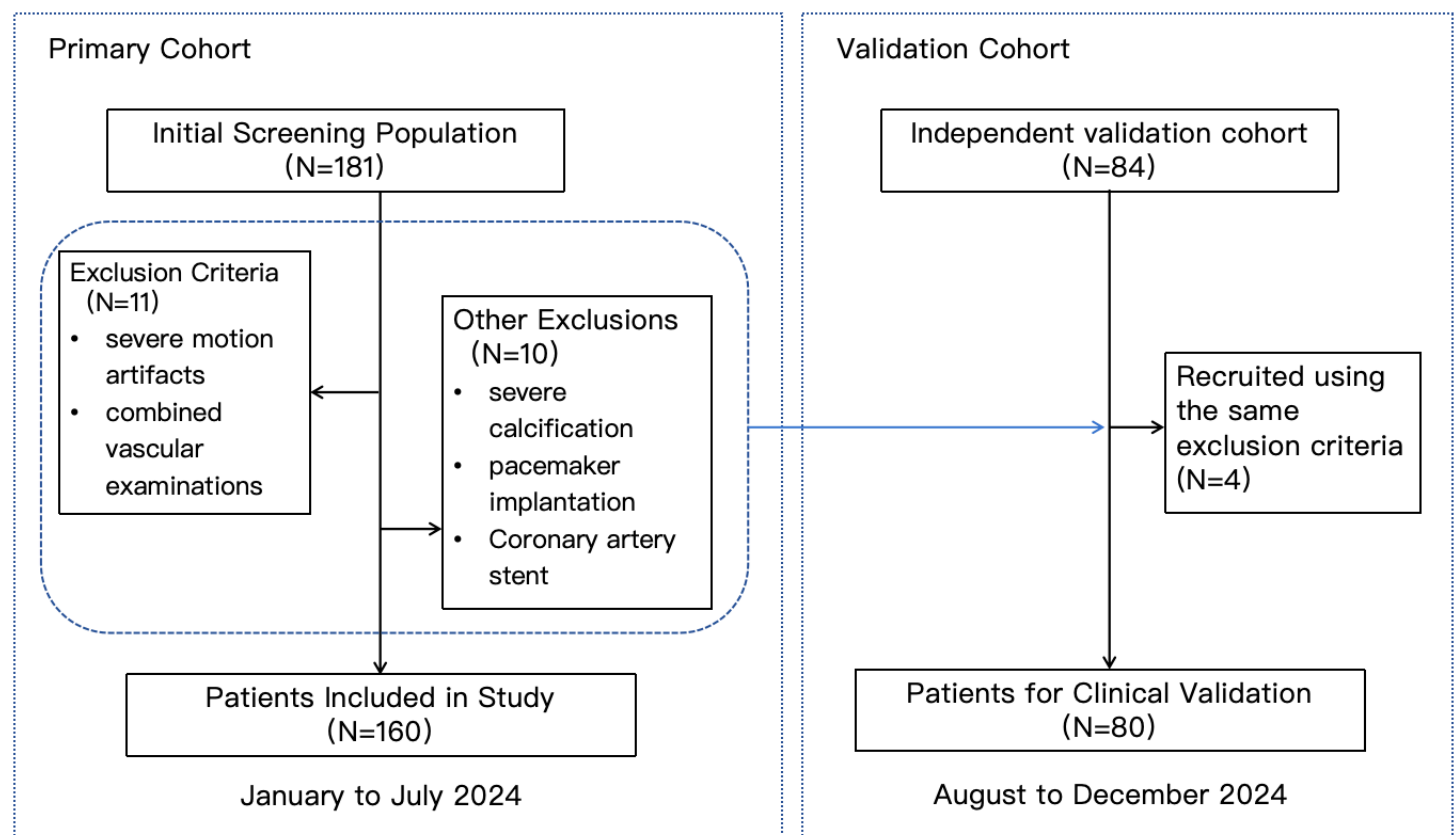


Figure 1

Flowchart shows study exclusion in both cohorts.

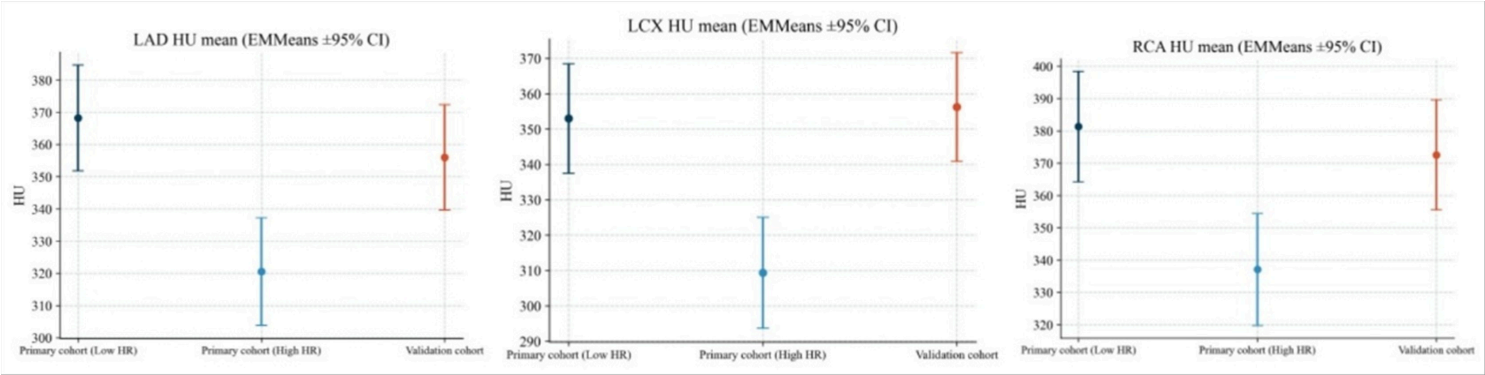


Figure 2

Figure 1. Estimated marginal means (EMMeans $\pm$ 95% CI) of luminal attenuation in LAD, LCX, RCA. Estimated marginal means of luminal attenuation (HU) in LAD, LCX, and RCA across the three groups, adjusted by ANCOVA. Error bars represent 95% confidence intervals.

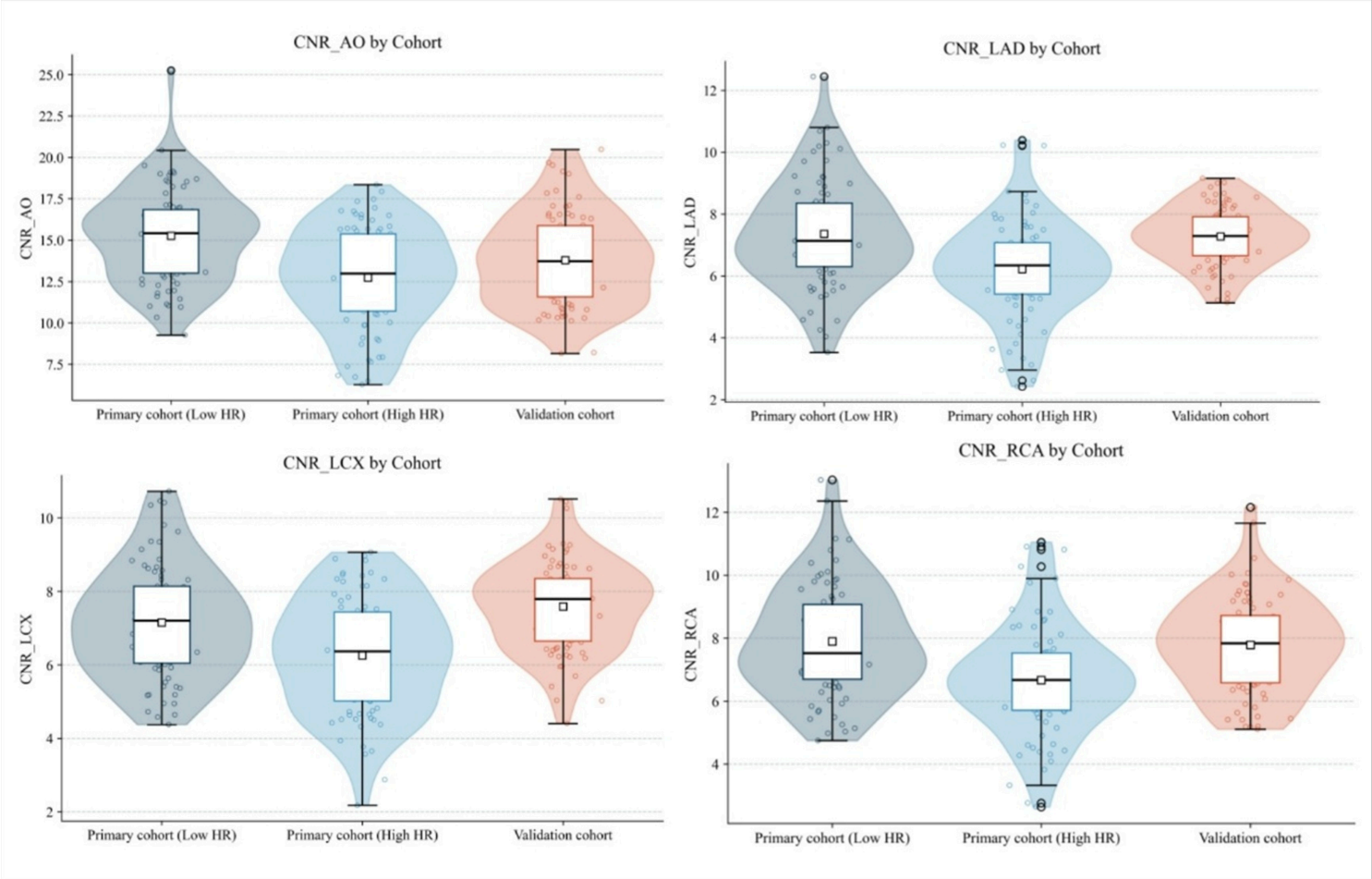


Figure 3

Figure 2. Violin-box plots of CNR distribution in AO, LAD, LCX, RCA. Violin-box plots showing the distribution of CNR values in AO, LAD, LCX, and RCA among the three groups. Boxes indicate interquartile range, horizontal line indicates median, square indicates mean.

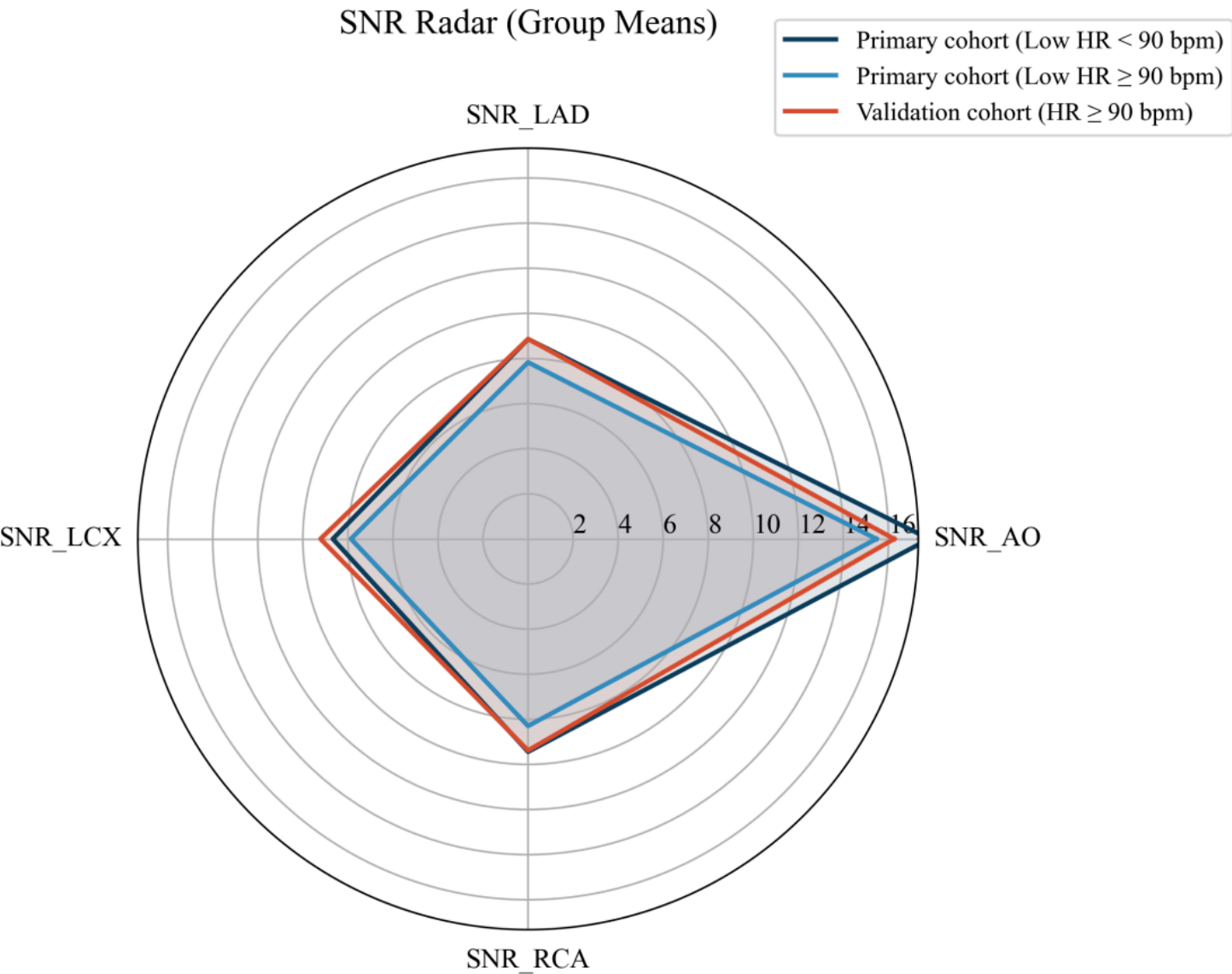


Figure 4

Figure 3. Radar plot of mean SNR values in AO, LAD, LCX, RCA across the three groups. Radar plot illustrating the mean SNR values of AO, LAD, LCX, and RCA among primary cohort and validation cohort: primary cohort (low HR <90 bpm), primary cohort (high HR ≥90 bpm), and validation cohort (≥90 bpm).

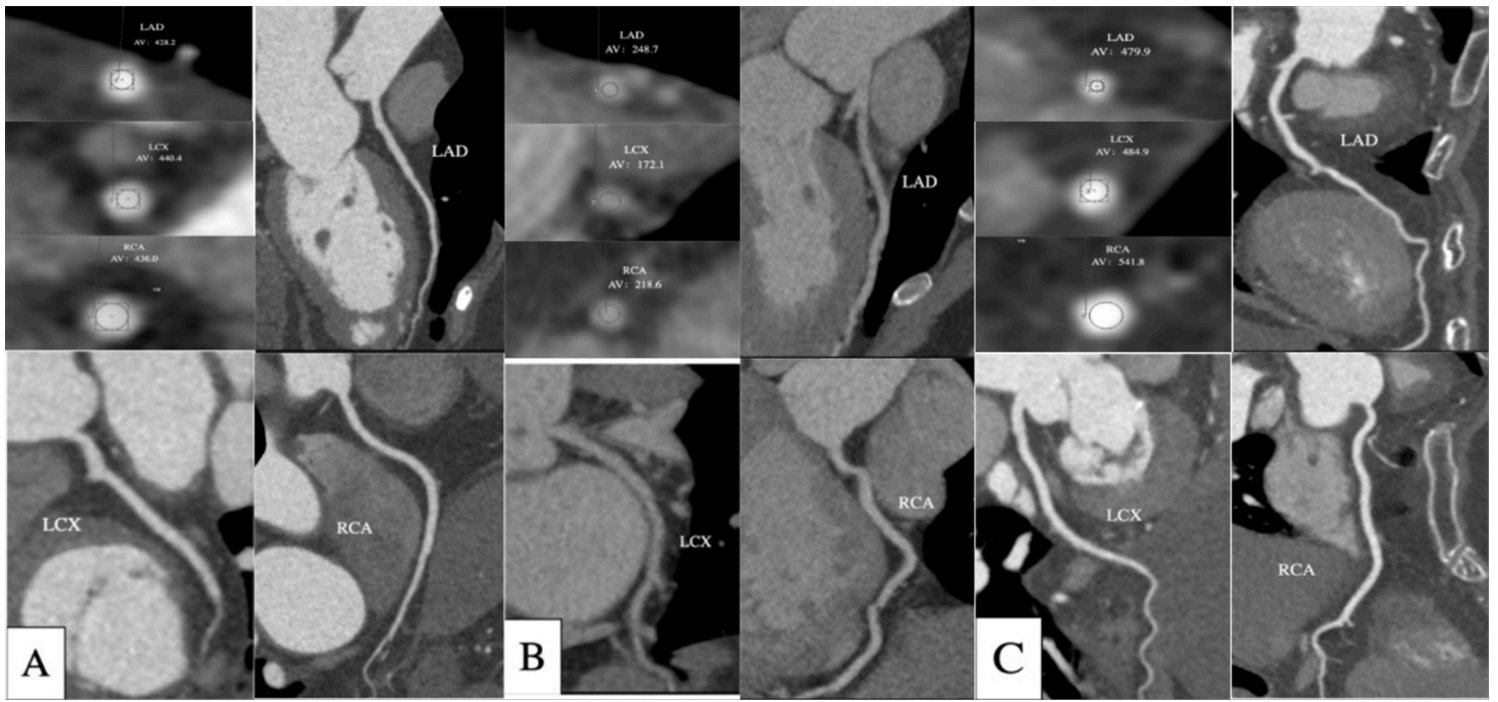


Figure 5

Figure 4. CPR images of the LAD, LCX, and RCA in representative patients:

(A)HR 65 bpm; LAD 428 HU, LCX 440 HU, RCA 436 HU.

(B) HR 111 bpm; LAD 249 HU, LCX 172 HU, RCA 219 HU.

(C)HR 109 bpm; LAD 480 HU, LCX 485 HU, RCA 542 HU.

A shows a low-HR patient using the traditional P3T protocol; B shows a high-HR patient with the traditional protocol; C shows a high-HR patient from the modified P3T validation cohort. The modified P3T high-HR protocol provided luminal enhancement comparable to traditional P3T the low-HR condition while minimizing motion artifacts.

Supplementary Files

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