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Influence of a new motion correction algorithm (CardioCapture) on the correlation between heart rate and optimal reconstruction phase

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ABSTRACT

Purpose: To investigate the effect of a new motion correction algorithm (CardioCapture) on the correlation between heart rate and optimal reconstruction phase by evaluating the impact of wide detector CT combined with CardioCapture on CCTA image quality.

Materials and methods: All cases were examined from April 2021 to September 2021. Two experienced radiologists scored these images on a four-point Likert scale. First, all images were divided into eight groups according to HR (at an interval of 5 bpm). The subjective score of images, the frequency of used CardioCapture, and the proportion of the diastolic reconstruction phase were compared in each group. Then, all cases were divided into two groups, one group was reconstructed using the automatic temporal reconstruction algorithm (Ephase) only, and the other group was reconstructed using the Ephase with the CardioCapture. The relationship between HR and the diastolic reconstruction phase was analyzed by the receiver operator characteristic curve (ROC).

Result: The data of 515 patients were studied. With the increase in HR, the subjective image score decreased, the frequency of CardioCapture increased, and the phase ratio of diastolic reconstruction decreased. When the HR was less than 70 bpm, the percentage of excellence image in each group surpassed 94.90%. The highest utilization rate of CardioCapture was 65.22%, and the lowest proportion of diastolic reconstruction was 72.46%. When 70 bpm $<$ HR $\leq$ 75 bpm, the image excellence rate was 90.43%, the CardioCapture utilization rate was 82.05%, and the diastolic reconstruction rate was 56.41%.When 75 bpm $<$ HR $\leq$ 80 bpm, the image excellence rate was 87.91%, the CardioCapture utilization rate was 80.65%, and the diastolic reconstruction was 6.45%.When the HR $>$ 80 bpm, the image excellence rate was 80.00%, the CardioCapture utilization rate was 75.00%, and the diastolic reconstruction rate was 22.50%. The best cut-off point between HR and the diastolic reconstruction ROC curve in the groups without CardioCapture was 65 bpm, while that in groups with CardioCapture was 68 bpm.

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Conclusion: The CardioCapture can effectively improve the image quality of CCTA with high HR. By maintaining the HR below 68 bpm and utilizing the prospective ECG-gated narrow phase axial scan, it is possible to ensure optimal image quality and concurrently reduce radiation dose.

Abbreviations

Multi-slice computed tomography (MSCT)
Coronary computed tomography angiography (CCTA)
Heart rate (HR)
Beats per minute (bpm)
Right coronary artery (RCA)
Left anterior descending artery (LAD)
Left circumflex artery (LCX)
Electrocardiogram (ECG)

1. introduction

Coronary heart disease is a prominent global cause of death. More and more randomized trials show that coronary computed tomography angiography (CCTA) is reliable in diagnosing of coronary artery-related diseases [1,2]. Non-invasive CCTA has emerged as the foremost clinical choice for the early evaluation and follow-up of coronary heart disease [3]. CCTA is a complex examination in multi-slice computed tomography (MSCT). High heart rate (HR), arrhythmia, heartbeat and respiratory movement will affect the image quality of CCTA. With the progress of MSCT technology development, gantry rotation time was faster; detector width was wider; the iterative algorithms were more popular, and motion correction algorithms were more efficient. These novel technologies empower CCTA with superior image quality, a wider gamut of applications, enhanced workflow convenience, and decreased radiation dosage [4,5].

The main factors affecting the quality of CCTA images were temporal resolution and induced motion artefacts [3]. How to improve temporal resolution was the focus of various manufacturers, and different devices have different architectures to improve temporal resolution. Both Canon Healthcare and GE Healthcare are equipped with 16 cm detector width. Canon utilizes multi-sector reconstruction technology to improve the temporal resolution, which increases with the number of sectors, However, the radiation dose increases proportionally [6]. GE improves the temporal resolution by employing a coronary artery motion correction algorithm. The temporal resolution depends on the motion correction level, and the correction is performed in a single cardiac cycle. Therefore, no additional radiation dose will be added [7]. Siemens' dual-source CT scanners enhance temporal resolution through a dual data acquisition system. The temporal resolution of the latest generation dual data acquisition system (Force, Siemens Healthcare, Germany) is the highest of all MSCT. Due to its 5.76 cm detector width, Force is unable to encompass the entire heart in a single axial scan. However, Force can achieve single cardiac cycle scanning through the utilization of large pitch technology, resulting in a significant reduction in radiation dose. This technique is not suitable for patients with arrhythmia [8].

Recently, a new 16 cm detector MSCT has been developed, incorporating a coronary artery motion correction algorithm based on artificial intelligence (CardioCapture, United-Imaging Healthcare, Shanghai, China). This innovative approach greatly improves the

Table 1
Study characteristics of the participants.

Patient's characteristics	Without CardioCapture group (n = 289)	With CardioCapture group (n = 226)	*Statistical value*	*p* Value
Sex				
Male	174	127	0.841[a]	0.359
Female	115	99		
HR (bpm)	58.60 ± 10.91	69.40 ± 10.84	−11.179	0.000
Age (years)	59.23 ± 10.54	57.50 ± 11.73	1.757	0.080
Weight (kg)	69.23 ± 11.37	68.81 ± 12.28	0.411	0.681
BMI(kg/m^2)	24.85 ± 3.07	24.76 ± 3.32	0.325	0.746
DLP (mGy × cm)	248.46 ± 162.11	273.90 ± 181.79	−1.675	0.094
ED (mSv)	3.48 ± 2.27	3.83 ± 2.55	−1.676	0.099
Scan cardiac cycle				
1 beat(n)	264	197	11.823[b]	0.002
2 beats(n)	16	28		
>2 beats(n)	9	1		

[a] : Chi-square test.
[b] : Fisher's precision probability test.

temporal resolution of CCTA. The present study aims to compare the effects of CardioCapture on CCTA image quality under different HR conditions and explore the correlation between CardioCapture and the heart rate threshold.

2. Material and method

2.1. Study participants

515 patients who underwent CCTA examination at Changhai Hospital of Shanghai of Naval Medical University from April 2021 to September 2021 were enrolled. The exclusion criteria were that patients were allergic to iodinated contrast agent, pregnancy, hyperthyroidism, renal insufficiency, and coronary artery bypass grafting. The clinical data of the patients are shown in Table 1. The Ethics Committee approved this study of the Changhai Hospital of Shanghai of Naval Medical University. All patients signed informed consent before the examination.

2.2. Coronary computed tomography angiography

All patients were examined with 320-row MSCT (uCT 960+, United-Imaging Healthcare, Shanghai, China). Patients with HR > 70 bpm were administered beta-blocker (Metoprolol Tartrate Tablets, AstraZeneca Pharmaceuticals Ltd., China) to regulate their HR 1 h prior to the examination. Beta-blocker dosage was administered based on the HR, HR < 75 bpm, 25 mg; 75bpm ≤ HR < 90 bpm, 50 mg; HR ≥ 90 bpm, 75 mg. Three minutes prior to the scan, patients were administered 0.6 mg of nitroglycerin (Nitroglycerin Tablets, Harbin Pharmaceutical Group Pharmaceuticals, Harbin, China), except for those with contraindications. Patients received respiratory training prior to the examination. The scanning range was from 10 mm below trachea bifurcation to the diaphragmatic surface of the heart. Ulrich double-barrel high-pressure syringe was used for individualized injection of iodine contrast agent. Non-ionic iodine contrast medium (iopamidol, 350 mgI/ml, Bayer Limited, China) was employed. The dosage of iodine contrast agent was determined as 23 mgI/kg/s (100 kV) or 25 mgI/kg/s (120 kV). The contrast medium was injected for 11 s, followed by 40 ml of normal saline. The automatic trigger scanning technique was utilized. The monitoring layer was positioned at the descending aorta of the aortic arch, with a trigger threshold was 120 HU. If the CT value of the region of interest reached the threshold, the scan was delayed for 5 s.

The prospective ECG gated axial scan mode was utilized in the CCTA scan. The tube voltage was set at 100–120 kV, the millisecond range was 80~200 mAs, the gantry rotation time was 0.25 s/r, the collimator width and scanning field were adjusted based on the size of the heart, the Z-axial coverage was 12–16 cm, the scanning field was 300 mm × 300 mm, and the matrix was 512 × 512 pixels. The display field of view was 200 mm × 200 mm, The reconstructed slice thickness was 0.5 mm, The interval between layers was 0.25 mm, and the filter function was KARL (Level 7). The patients were categorized into three groups before the scan: low HR group (HR ≤ 65 bpm), Moderate HR group (65 bpm ≤ HR < 80 bpm) and high HR group (HR ≥ 80bpm). 70%–85% R–R interval was scanned in the low HR group, 35%–85% R–R interval in the moderate rate group and 30%–90% R–R interval in high HR group. The phase of the final diagnostic image was divided into diastolic reconstruction and systolic reconstruction. R–R interval ≥50% was the diastolic phase and R–R interval <50% was the systolic phase.

2.3. Image processing

After completing the scan, automatic optimal phase reconstruction (ePhase, United-Imaging Healthcare, Shanghai, China) was employed as the first step, including full cycle reconstruction, systolic reconstruction and diastolic reconstruction. The artificial phase was applied to images with unsatisfactory results. If the image exhibited motion artefacts, CardioCapture was utilized for reconstruction. Fig. 1 illustrates the post-processing of patient's CCTA data, depicting the utilization of ePhase and cardiocapture. According to the diagnostic images, the patients were categorized into groups without CardioCapture and groups with CardioCapture. All patients were categorized into eight groups with five bpm as the interval to investigate the relationship between different HR and the optimal

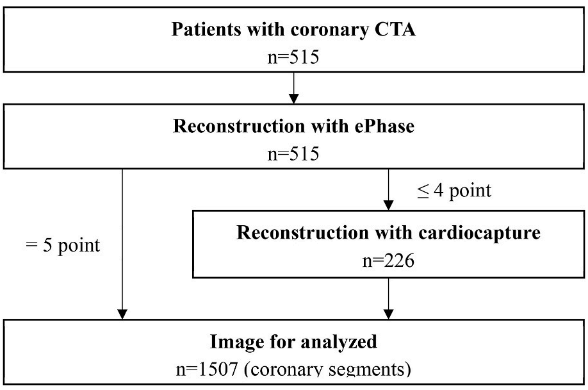

Fig. 1. Flow chart of post-processing of patient data in this study.

reconstruction phase, as shown in Table 2.

CardioCapture is an innovative motion correction technology that has been developed to address the issue of motion artefacts in cardiac imaging. Specifically in the context of coronary artery examinations using the uCT 960+ system. During a coronary artery scan, patient movement can introduce motion artefacts, leading to blurry or distorted images. These artefacts can hinder accurate diagnosis and assessment of coronary artery disease. CardioCapture leverages AI-assisted motion correction techniques to minimize these artefacts and enhance the quality of the imaging results. The underlying principle of CardioCapture is centerline-based motion tracking and estimation. By tracking the centerline positions of the coronary arteries, it becomes possible to approximate the motion fields from one phase to another that were captured in the imaging process. This approach specifically focuses on correcting the motion around the coronary arteries, which are of utmost importance in coronary artery exams. To facilitate the centerline extraction of the coronary arteries, CardioCapture utilizes deep learning techniques with convolutional neural networks (CNN). CNNs have proven to be highly effective in image processing tasks, and in this study, a V-Net with dilated convolution [9] is employed for coronary artery segmentation. This segmentation process helps identify and isolate the coronary artery regions from the surrounding anatomy. Once the coronary arteries have been segmented, an optimization procedure is applied to extract a refined and smoothed centerline from the segmented coronary artery mask. This centerline provides crucial information about the motion of the coronary arteries throughout the cardiac cycle. In the next step, a multi-level motion vector field generation scheme is employed. This scheme allows for the detection and characterization of motion at different scales, providing a comprehensive understanding of the motion patterns in the coronary arteries. The integration of CardioCapture with the uCT 960+ system offers significant benefits in terms of both efficiency and accuracy.

By combining CardioCapture with ePhase, a technique used for capturing cardiac motion phases, the entire CCTA examination process can be automated. This automation reduces the need for manual intervention and enables faster and more accurate examinations.

2.4. Subjective image quality

All the data were uploaded to a processing workstation (uWS-CT, United Imaging Healthcare, Shanghai, China) for volume rendering, curved planar reformation and maximum intensity projection processing. Two experienced radiologists graded all images. The three major branches of the coronary arteries evaluated were the right coronary artery (RCA), left anterior descending artery (LAD) and left circumflex artery (LCX). The image quality scoring standard adopts a four-point system [10]: 4 point indicate excellent, no motion artefacts, clear outline of the blood vessel wall; 3 point indicate good, slight artefacts of the vessel wall, and good image quality; 2 point indicate moderate, motion artefacts slightly affect the display of the vessel wall; 1 point indicates poor, severe motion artefacts, and unable evaluate blood vessels. In case of score disparities, the two readers reached a consensus. The diagnosable segments were a subjective score of 2 or higher.

2.5. Radiation dose

The dose-length product (DLP) automatically generated by the CT scanner console was recorded, and the effective dose was calculated as the product of DLP multiplied by a conversion coefficient k [$k = 0.014$ mSv $\times$ (mGy $\times$ cm)$^{-1}$].

2.6. Statistical analysis

MedCalc® Statistical Software version 20.0.4 (MedCalc Software Ltd, Ostend, Belgium) was utilized for statistical analysis. The measurement data, conforming to a normal distribution, were expressed as mean ± standard deviation. The counting data were expressed by frequency and percentage. The normal distribution was evaluated using Normal Q-Q Plots. The Chi-square test was used to compare the subjective scores on image quality among different groups. If the expected frequency was less than 5, the Fisher's exact test was used. An independent sample *t*-test is utilized when the data follows a normal distribution and homogeneity of variance is

Table 2
The image excellence rate, the frequency of used CardioCapture and the proportion of diastolic reconstruction phase were compared in different HR groups.

	Excellent rate (%)	Frequency of used CardioCapture (%)	Proportion of diastolic reconstruction phase (%)
All HR	94.29% (1421/1507)	43.88 (226/515)	78.64% (405/515)
HR $\leq$ 50	98.00% (147/150)	5.77 (3/52)	94.23% (49/52)
50 $<$ HR $\leq$ 55	97.16% (211/211)	12.68% (9/71)	98.59% (70/71)
55 $<$ HR $\leq$ 60	96.94% (285/294)	24.00% (24/100)	99.00% (99/100)
60 $<$ HR $\leq$ 65	96.12% (322/335)	51.33% (58/113)	92.04% (104/113)
65 $<$ HR $\leq$ 70	94.90% (186/196)	65.22% (45/69)	72.46% (50/69)
70 $<$ HR $\leq$ 75	90.43% (104/115)	82.05% (32/39)	56.41% (22/39)
75 $<$ HR $\leq$ 80	87.91% (80/91)	80.65% (25/31)	6.45% (2/31)
HR $>$ 80	80.00% (92/115)	75.00% (30/40)	22.50 (9/40)
Statistical value (χ2)	72.852	145.914	245.37
P value	$<$0.001	$<$0.001	$<$0.001

achieved. The interobserver agreement was analyzed with a simple Kappa coefficient (kappa ≥0.75: excellent agreement; 0.40 ≤ kappa <0.75: good agreement; and kappa <0.40: poor agreement). The receiver operating characteristic (ROC) analyzed the relationship between HR and the diastolic reconstruction phase. Calculate the area under the curve (AUC), the *p*-value, and the 95% confidence interval. A two-sided *p*-value <0.05 was deemed to be statistically significant.

3. Results

3.1. Study population characteristics

A total of 515 patients completed the CCTA examination, the average HR was 63.34 ± 12.12 bpm (HR range,27–155 bpm). The study cohort comprised 289 males and 226 females, and the average age was 58.47 ± 11.10 years (age range,28–89 years). The best reconstruction phase distribution histogram of all HRs was shown in Fig. 2(A), while the best reconstruction phase distribution histograms of HRs ≤65 bpm, 65 bpm < HRs ≤80 bpm, and HRs >80bpm were shown in Fig. 2(B-D). The optimal reconstructed phase was predominantly observed during diastole, with the highest frequency occurring at the 70%–75% phase, followed by the 75%–80% phase. When HR ≤ 65 bpm, the diastolic phase accounted for 95.83% (322/336), and 78.27% (263/336) of the optimal phases falling within the 70%–80% phase. When 65 bpm < HR ≤ 80 bpm, diastole accounted for 54.24% (74/139), with 46.76% (65/139) of the optimal phases falling within the 70%–80% phase. When HR > 80 bpm, the systolic phase accounted for 77.50% (31/40), with 70.00% (28/40) of the best phases falling within the 35%–45% range of phases.

3.2. Subjective image quality

The CardioCapture was utilized in 43.88% of the CCTA reconstruction. The comparison of the image excellence rate, the frequency of used CardioCapture and the proportion of diastolic reconstruction phase in different HR groups were presented in Table 2. As the HR increased, the image excellence rate decreased, the frequency of CardioCapture usage increased, and the proportion of diastolic reconstruction phase decreased. When 65 bpm < HR ≤ 70 bpm, the image excellence rate was 94.90%, the frequency of CardioCapture usage was 65.22%, and the proportion of diastolic reconstruction phase was 72.46%. With the increase in HR, the image excellence rate reached the lowest after HR > 80 bpm, The frequency of CardioCapture usage was the highest (82.05%) when 70 bpm < HR ≤ 75 bpm, and the proportion of diastolic reconstruction phase was the lowest (6.45%) for HR between 75 bpm and HR ≤ 80 bpm. Motion artefacts and edge blurring of blood vessels (arrows) were observed in Fig. 3(A, C, E, and G) following the application of the ePhase

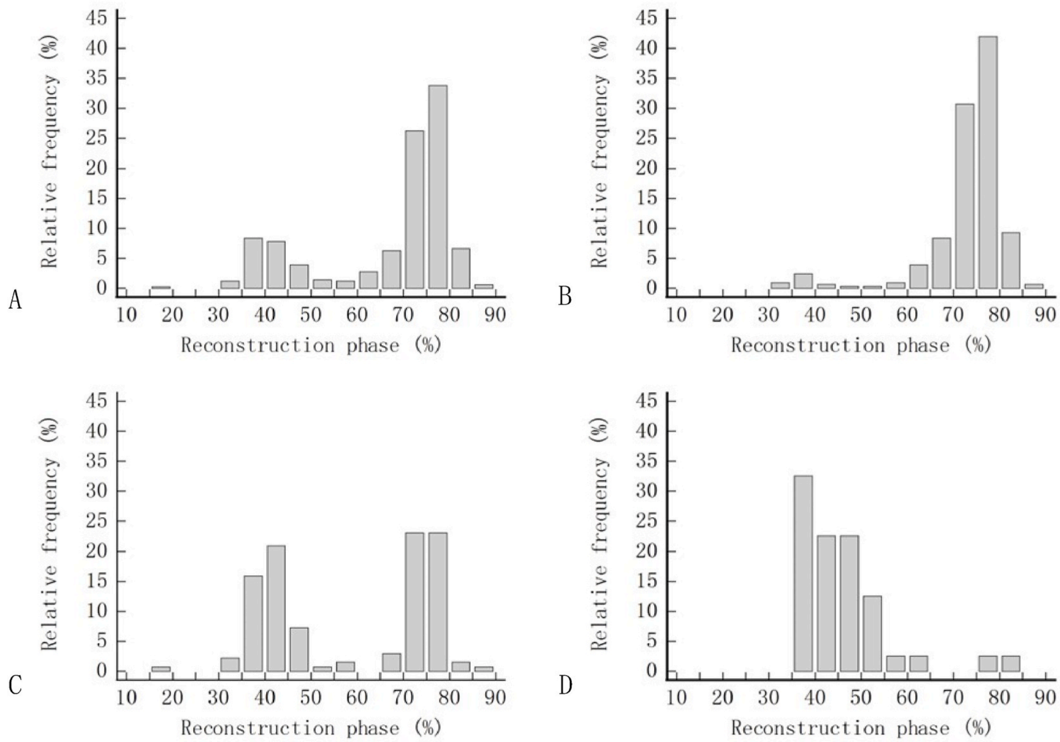

Fig. 2. Histogram of the phase distribution of the optimal reconstruction phase under different HR conditions. **A** shows the best reconstruction phase distribution histogram of all HRs, and **B,C,D** shows the best reconstruction phase distribution histogram of HR ≤ 65 bpm, 65 bpm < HR ≤ 80 bpm and HR > 80bpm, respectively.

technique. In contrast, when the cardiocapture technique was used, the same blood vessels (arrows) in Fig. 3(B, D, F, and H) appear clear and sharp.

Two observers evaluated 1507 coronary segments in 515 patients. The subjective consistency of RCA, LAD and LCX images were 0.86, 0.81 and 0.81, respectively, and they exhibited excellent agreement. The average subjective scores of RCA, LAD and LCX images were (3.95 ± 0.23), (3.92 ± 0.28) and (3.95 ± 0.22), respectively. The subjective scores of three branches under different HR conditions were compared in Table 3. The subjective score decreased with the increase in HR. There was a significant difference between groups in RCA and LCX. and no significant difference between groups in LAD.

3.3. Relationship between HR and diastolic reconstruction

The relationship between heart rate (HR) and the diastolic reconstruction phase was analyzed using ROC analysis (Fig. 4) in groups without CardioCapture and groups with CardioCapture. When analyzed by groups without CardioCapture, the area under the curve was 0.856, $p < 0.001$. Youden index J was 0.686, and the best cut-off value is 65(HR ≤ 65 bpm was considered a reasonable diastolic scanning range). In the groups with CardioCapture, the area under the curve was 0.850, $p < 0.001$. Youden index J was 0.564, and the best cut-off value was 68(HR ≤ 68 bpm was considered a reasonable diastolic scanning range).

4. Discussion

The results indicate that the use of 320-row MSCT with CardioCapture can meet the requirements for the majority of CCTA exams. When HR ≤ 70 bpm, 94.9% of the images achieved excellence, and 72.46% of the patients had the optimal reconstruction phase in diastole. When 70 bpm < HR ≤ 75 bpm, 90.43% of the images achieved excellence, and only 6.45% of the patients had the optimal reconstruction phase in diastole. Compared to the groups without CardioCapture, the threshold of HR for diastolic reconstruction phase increased from 65 bpm to 68 bpm.

The progression of CCTA imaging is driven by continuous technological advancements of CT equipment. The upgrading of hardware and software results in notable changes in the scope of application and workflow of CT examination, particularly in CCTA imaging [11]. The market focuses on three significant ways to improve CCTA images: advancements at the hardware level, improvements in scanning modes, and innovations in software technology [12]. Hardware level improvements primarily involve upgrades in the gantry rotation time and detector width, which can affect the temporal resolution of CT imaging. The increase in CT gantry rotation time supports the application of HR with a higher threshold value. S. Achenbach et al. used first-generation Dual-source MSCT with a gantry rotation time of 0.33 s/r, which required an upper HR control of 49 bpm, and second-generation Dual-source MSCT with a gantry rotation time of 0.28s/r, requiring an upper HR control of 60 bpm [13,14]. In another study, F. Morsbach et al. raised the upper threshold of HR to 70 bpm when scanning with a gantry rotation time of 0.25s/r on third-generation dual-source MSCT [15]. Dual-source CT boasts the highest single-sector temporal resolution in the industry. With the increase in gantry rotation

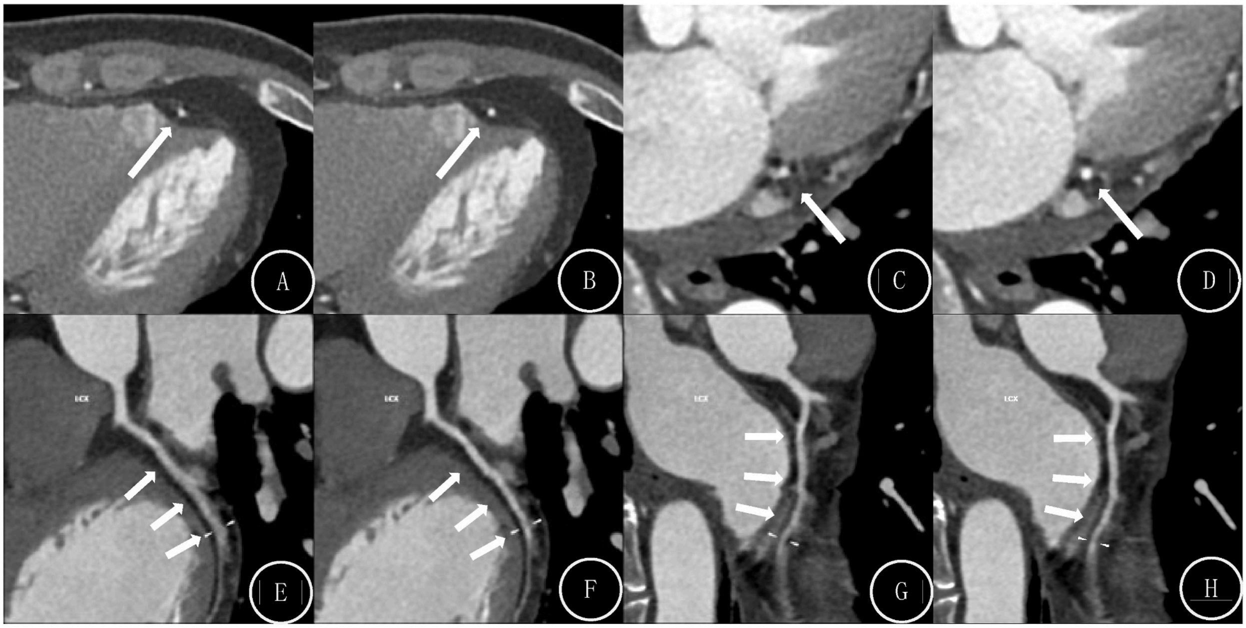

Fig. 3. Representative images were processed with Ephase and CardioCapture. **A, C, E, G** After ePhase, the axial image and curved planar reformation (CPR) image (arrow) show motion artifact and blurred edge. **B, D, F, H** After CardioCapture, the axial and CPR image (arrow) are clear and sharp.

Table 3
Subjective scores were compared in different HR groups.

	RCA	LAD	LCX
All HR	3.95 ± 0.23	3.92 ± 0.28	3.95 ± 0.22
HR ≤ 50	4.00[a]	3.94 ± 0.24	4.00[b]
50 < HR ≤ 55	4.00[a]	3.93 ± 0.26	3.99 ± 0.12[b]
55 < HR ≤ 60	3.97 ± 0.17[a]	3.96 ± 0.20	3.98 ± 0.14[b]
60 < HR ≤ 65	3.96 ± 0.19[a]	3.94 ± 0.28	3.96 ± 0.23[b]
65 < HR ≤ 70	3.97 ± 0.17[a]	3.91 ± 0.28	3.97 ± 0.18[b]
70 < HR ≤ 75	3.85 ± 0.37	3.90 ± 0.31	3.97 ± 0.16[b]
75 < HR ≤ 80	3.94 ± 0.25	3.84 ± 0.37	3.86 ± 0.35
HR > 80	3.78 ± 0.48	3.84 ± 0.37	3.76 ± 0.44
Statistical values(*H*)	5.194	2.151	5.862
P value	<0.001	0.177	<0.001

RCA: right coronary artery, LAD: left anterior descending artery, LCX: left circumflex artery.
[a] Compared with group 70 < HR ≤ 75 and group HR > 80, the difference was statistically significant. [b]: Compared with group 75 < HR ≤ 80 and group HR > 80, the difference was statistically significant.

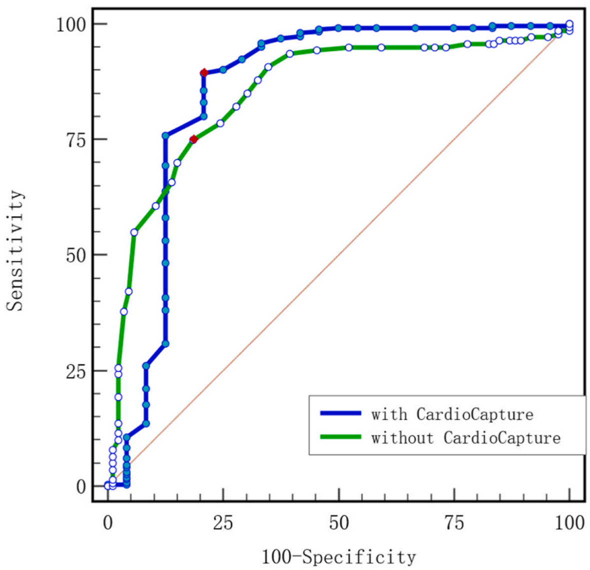

Fig. 4. The relationship between HR and optimal diastolic reconstruction phase were analyzed by ROC. The green line shows the ROC curve of groups without CardioCapture. The area under the curve was 0.856. and the sensitivity, specificity and the best cut-off value of the scanning phase selected by HR were 89.43%,79.17% and 65, respectively. The blue line shows the ROC curve of groups with CardioCapture. The area under the curve is 0.850, and the sensitivity, specificity and best cut-off value of the scanning phase selected by HR are 75%,81.4% and 68, respectively.
Receiver operating characteristic (ROC) analyses for Ephase with CardioCapture and without CardioCapture in relation to optimal diastolic reconstruction phase. Area under the curve for Ephase with CardioCapture (AUC = 0.850) have no significantly difference than that for Ephase without CardioCapture (AUC = 0.856; z = 0.0891, p = 0.929). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

time, the applicable threshold of HR is significantly increased. However, due to the limited detector width, image quality cannot be guaranteed when the patient's heart rate is irregular or unable to breathe. The current widest detector width in the industry is 16 cm, which can cover the entire heart region in a single rotation. When coupled with ultra-high rotation speed, wide-detector technology can more effectively tackle the challenges in CCTA imaging for patients with irregular heart rates or patients unable to breath-hold instructions [4,15]. This technology simplifies the workflow and significantly reduces the requirements for patients [11]. However, its direct impact on the HR threshold is limited.

The advancement of CT equipment hardware will lead to changes in CT scanning modes, which are an essential way to balance the relationship between image quality and radiation dose. In this study, the latest generation of 320-row MSCT was used to cover the entire heart in one single beat with the fastest gantry rotation time of 0.25/r. This device was independent of HR, HR variability, and respiratory training. It was considered the most efficient and promising system to fulfill the requirements of cardiac scanning [5,17]. The MSCT with CardioCapture can improve the temporal resolution of CCTA up to 21 ms [18], enabling single-beat CCTA imaging at arbitrary HR by effectively suppressing coronary motion artefacts. Heart motion and respiratory motion exhibit different motion characteristics. The velocity of coronary motion induced by respiratory motion is considerably greater than that induced by the heartbeat. Single cardiac cycle imaging can be achieved using a 16 cm detector MSCT. The final image can ignore the artefacts caused by normal respiration [4,16].

Choosing the appropriate CCTA scanning mode is crucial, considering the hardware characteristics of CT. The radiation dose of the prospective ECG-gated axial scan was 80% lower than that of the retrospective ECG-gated spiral scan. Moreover, the radiation dose of the prospective ECG-gated narrow phase padding scan was 80% lower than that of the prospective ECG-gated wide phase padding scan. The minimum velocity of diastolic motion increases with an increase in HR, resulting in a decrease in the image quality of the diastolic reconstruction phase with the increase in HR. Although both the systolic and diastolic phases of cardiac exercise can provide diagnostic CCTA images and meet clinical coronary heart disease screening, the latest study found that in the diagnosis of coronary ischemic disease, the diagnostic efficacy of Fractional Flow Reserve (FFR) based on CCTA in the diastolic phase is better than that in the systolic phase. Especially for the lesions with FFR <0.7, the diastolic FFR based on CT was more similar to the FFR based on DSA [19]. Obtaining high-quality diastolic images under higher HR was the key to a prospective ECG-gated narrow diastolic phase scan, so it is essential to determine the optimal HR threshold for the diastolic reconstruction phase.

The advancements in CT equipment software primarily manifest in the updates of iterative reconstruction algorithms and motion correction algorithms. The purpose of iterative reconstruction algorithms is to improve image quality and reduce artefacts, particularly in situations with low radiation dosage where it can achieve a comparable image quality to the previous generation of reconstruction algorithms [20]. However, it cannot change the heart rate threshold, so this technology is not within the scope of this study.

Motion correction algorithms have a significantly impact on the image quality of CCTA, and it is the primary focus of this study. Previous methods of dynamic compensation for motion correction in image processing relied on image registration or motion estimation to reduce motion artefacts. Some 3D-3D non-rigid image registration-based methods have exhibited excellent results in motion correction [21]. However, in the presence of substantial motion artefacts, registration errors may arise, resulting in a degradation of motion correction. In order to improve image quality, a motion vector field (MVF) estimation technology using iterative motion correction methods has been introduced [22], aimed at minimizing motion artefacts measures. The SnapShot Freeze (SSF) motion correction algorithm from GE Healthcare, which restores lumen based on the vascular path and velocity in multiple adjacent cardiac cycles, is presently more mature in the market. However, this algorithm necessitates a substantial amount of computation and carries a protracted reconstruction time, presenting limitations in addressing vascular variation and stenosis.

Currently, the research is focused on the application of deep learning to CCTA imaging. Two methods are used to correct motion artefacts in CCTA [23]. The first method involves reconstructing the images without modeling the actual motion of the heart, and the artefacts are corrected through post-processing using deep learning techniques. The second method involves training a neural network to predict the motion of the coronary arteries and using this prediction to correct the motion artefacts. In this study, a novel artificial intelligence-assisted motion correction algorithm called "CardioCapture" was used, the algorithm involved inserting a trained neural network into each stage of the motion correction process, which proves to be a superior solution [11,17].

CardioCapture mainly focuses on motion correction around the coronary arteries and utilizes an optimized algorithm called V-Net with dilated convolution for coronary artery segmentation [9]. Furthermore, it employs an optimization step to extract a smooth centerline from the segmented coronary artery mask. Finally, A scheme is employed for the generation of a multi-level motion vector field to capture motion across varying scales. Previous research has theoretically shown that CardioCapture combined with automatic reconstruction and temporal information technology can achieve automated CCTA examinations, and improve examination efficiency and accuracy [11]. However, the impact of CardioCapture technology on the threshold of HR applicability has not been studied. H. Machida et al. first reported the study using a motion correction algorithm (Snap Shot Freeze; GE Healthcare) for CCTA [24]. A retrospective ECG-gated spiral scan combined with motion correction algorithm was used on 64-slice CT scanner with gantry rotation time of 0.35 s/r. The threshold of HR was increased from 64 bpm to 79 bpm. It is suggested that reliable image quality can be obtained using the prospective ECG-gated axial scan during diastole when the heart rate (HR) is less than 65 bpm. The study conducted by Ching-Ching Yang et al. showed that in 256-slice MSCT with a gantry rotation time of 0.28 s/r and a Z-axial coverage of 16 cm, the threshold of HR for diastolic reconstruction was 67 bpm. When 63 bpm $\leq$ HR $<$ 67 bpm or HR $\geq$ 68 bpm, the proportion of the diastolic reconstruction phases were 89.3% and 71.7%, respectively. After using the motion correction algorithm, the diagnostic rate of image is 100%, while the excellent rate was only 19.44% and 7.8%. In our study, when 65 bpm $<$ HR $\leq$ 70 bpm, the proportion of diastolic reconstruction phase was 72.46%, and the excellent rate of image was 94.90%. However, our conclusion from the ROC analysis was 68 bpm. When 65 bpm $<$ HR $\leq$ 70 bpm, the image score was better than that of Ching-Ching Yang [25]. This may be related to the evaluation criteria of image quality. Different evaluation criteria for images will affect the excellence rate of the images and affect the HR threshold for diastolic reconstruction. If the diagnostic criteria of image quality were lowered, the diastolic reconstruction phase could be used under higher HR. Therefore, the HR threshold for the diastolic reconstruction phase will also change. In general, maintaining the HR below 68 bpm and adopting the prospective ECG-gated narrow phase axial scan ensures excellent image quality and significantly reduces radiation dose. This study updates the applicable heart rate range of wide-detector CT low-dose scan mode (prospective ECG-gated narrow phase axis scan), which can provide theoretical guideline for clinical frontline operators.

5. Limitations

Firstly, this study only evaluated the image quality and did not compare it with the data of invasive coronary angiography. Secondly, three branches of the coronary artery were evaluated, but not all the coronary artery segments. Thirdly, there were four levels of CardioCapture (level 3,5,7 and 9); we did not reconstruct and compared them separately. Finally, the lower-dose scanning technique was not used in this study.

6. Conclusion

In conclusion, the research findings suggest that cardiocapture technology is an effective algorithm for correcting motion of coronary arteries. It can improve the temporal resolution of CCTA imaging and improve image quality, especially in patients with high heart rates. Combining cardiocapture technology with a 16 cm-wide detector and a gantry rotation time of 0.25s/r can improve the image quality of diastolic CCTA in high heart rate patients within a single cardiac cycle. Based on our research, the CardioCapture could increase the HR threshold of the prospective ECG-gated narrow-phase diastolic scan from 65 bpm to 68 bpm, providing data support for the clinical utilization of this technique.

Ethical approval

This study was reviewed and approved by the Ethics Committee of Shanghai Changhai Hospital, with the approval number: CHEC2020-164. Informed consent was not required for this study because it was a retrospective study, and all patients had previously signed informed consent forms for CCTA-enhanced examinations.spital, with the approval number: CHEC2020-164. Informed consent was not required for this study because it was a retrospective study, and all patients had previously signed informed consent forms for CCTA-enhanced examinations.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Wei Yin: Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ruimin Xu:** Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Binghui Zhao:** Validation, Resources, Project administration, Methodology, Investigation, Data curation. **Shuilian Liu:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Minjie Wang:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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.

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