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The role of latency period in quality management for free-breathing coronary wall MRI

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Abstract

Purpose—To determine the effects of the latency period on the performance of free-breathing coronary wall MRI

Materials and methods—With the approval of IRB, 70 participants were recruited for coronary wall magnetic resonance imaging (MRI) and provided written informed consent. In 35 subjects, right coronary segments (RCA1–3) were imaged first; in the remaining subjects, the left coronary segments (LM and LAD1–3) were imaged first. The images were classified into groups; group 1 contained right coronary images from the subjects whose right coronary segments were imaged first and left coronary images from the subjects whose left coronary segments were imaged first. Group 2 contained the other coronary segments. The image scores (ranked 1–3), latency periods, drift of the position of the navigator (NAV), scan efficiency were compared between image groups.

Results—Image group 1 has higher scores (1.66 ± 0.55 vs. 1.46 ± 0.51), shorter latency periods (32.04 ± 4.24 minutes vs. 44.22 ± 5.57 minutes), lower drift in the location of the NAV (1.90 ± 1.27 mm vs. 2.61 ± 1.71 mm) and higher scan efficiency ($32.7 \pm 7.6\%$ vs. $29.9 \pm 7.9\%$) than group 2.

Conclusion—Long latency periods have a significantly negative impact on the image quality of coronary wall MRI.

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Keywords

Coronary wall MRI; image quality; latency period

Introduction

In clinical practice, culprit plaques on the coronary wall are recognized as direct sources of adverse cardiovascular events, including acute coronary syndrome (ACS), myocardial infarction (MI), congestive heart failure and cardiac death^{1,2}. Magnetic resonance imaging (MRI) has become a promising imaging method that has been used to screen the coronary plaques for over a decade³. Based on existing free-breathing MRI schemes, a coronary wall image is reconstructed with *k*-space data acquired during short "cardiac motion free" time windows over multiple heart beats and respiratory cycles⁴. In addition, a multi-plane coronary wall MRI image involves complex preparations, including localization and calculation of scan parameters, which typically require a long time to complete. Although subjects with claustrophobia (an anxiety status) have routinely been excluded from clinical MRI examinations, a common argument is that, even in normal individuals, a long scan period will induce body movements that degrade the MRI image quality by creating image artifacts. Therefore, long scan duration is usually considered an unaffordable luxury for coronary wall MRI.

Recent technical advances have been applied to shorten the sequence running times and improve the effectiveness of coronary wall MRI⁵⁻⁷. There remains, however, a latency period during which necessary procedures must be completed to accomplish a coronary MRI scan. However, the role of the latency period and the clinical implications of increased latency period time on MRI quality management (QM) have never been thoroughly examined. It is unknown, therefore, whether the latency period affects the image quality and in what ways coronary wall MRI might be affected by the latency time. The knowledge gap exists mainly because it is difficult to identify and quantify a causal relationship between the latency period and imaging outcomes.

Based on our experiences with coronary wall MRI, we hypothesized that a long latency time may affect the image quality due to adverse changes of certain technical and physiological conditions, such as irregular breathing patterns, in human subjects. The aim of the present study was to prospectively determine the relationships between the length of latency time and image quality of two-dimensional (2D), noncontrast, multi-plane, free-breathing coronary wall MRI images.

Materials and methods

Study participants

This study complied with HIPAA regulations. Following the approval of the institutional review board (IRB), 70 asymptomatic elderly participants of Chicago Healthy Aging Low-Risk Magnetic Resonance Angiography Study (CHARISMA) without documented history of cardiovascular disease, including 38 male subjects (mean age 72.05 ± 3.95 years old,

range 66 – 84 years old) and 32 female subjects (mean age 72.28 ± 5.06 years old, range 65 – 83 years old), were recruited and underwent coronary wall MRI⁸. Written informed consent was provided by all participants. Exclusion criteria included: heart rate (HR) > 65 beats/minute, breathing frequency > 24 breaths/minute and other factors known to interfere with MRI.

MRI facility

For all participants in this study, the MRI examinations were performed by 2 certified clinical MRI technicians on a 1.5 T scanner (SIEMENS, MAGNATOM, Espree, Germany) with a 6-channel cardiac phased-array coil. During the coronary wall MRI, participants were told to keep still and breath normally.

General coronary wall MRI parameters

A 3-plane, rapid localization sequence was run to provide anatomic orientation for the entire scan. A black-blood half-Fourier acquisition single-shot turbo spin-echo sequence was used to obtain images using standard 4-chamber and short-axis display orientations. A 2D balanced steady-state free precession (true FISP) sequence was used to take cardiac cine images (22 reconstructive cardiac phases) with a 4-chamber view of the heart. The rest period (at mid-diastole) of cardiac motion was determined using 4-chamber cine images⁷. A navigator (NAV)-gated, electrocardiography (ECG)-triggered, fat-saturated, T2-prepared, segmented three-dimensional (3D) SSFP sequence was used to perform bright-blood whole-heart coronary magnetic resonance angiography (MRA). The NAV signal for respiratory gating was acquired using a spin-echo readout. A 90° pulse for excitation was planned in the sagittal view, and a 180° pulse for refocusing was planned in the sagittal view, tilted (30°) toward the coronal plane ($S > C$). The acceptance window was ± 2.5 mm. Imaging data that had the liver-lung boundary within this distance window were accepted. A motion-adaptive gating algorithm was applied to detect the drift of respiratory motion and to dynamically update the acceptance window. The 3D *k*-space data were collected using a linear order in both the phase-encoding direction and the partition-encoding direction. The in-plane resolution was 1.1×1.1 mm². The slice thickness was 0.7 mm (interpolated from 1.4 mm). Other imaging parameters included TR/TE = 3.7/1.7 ms, flip angle = 90°, bandwidth = 870 Hz/pixel and parallel acquisition factor = 2. Multiplanar reformations (MPR) were performed on 3D MRA images to localize the left main artery (LM), left anterior descending artery (LAD) and right coronary artery (RCA). Perpendicular to the long axis of the vessel and beginning at 5 mm from the origin of the vessel, cross-sectional black-blood images of the coronary arteries were acquired using a NAV-gated, ECG-triggered, double inversion recovery (DIR)-prepared 2D turbo-spin-echo (TSE) sequence. A spectral-selective adiabatic inversion recovery (SPAIR) pulse was used to improve the contrast between the coronary wall and epicardial fat by suppressing fat signals. We acquired 1 slice of the LM, 3 slices of the LAD, and 3 slices of the RCA at 5-mm intervals⁷. The coronary wall imaging parameters for all coronary segments of a single subject include the following: TR/TE = 800/33 ms, bandwidth = 305 Hz/Pixel, matrix = 448×448 , field of view (FOV) = 420×420 mm², and slice thickness = 4 mm. For coronary MRA and coronary wall MRI, the data acquisition window was individually set so as not to exceed the coronary rest period duration and to begin after the onset of the coronary rest period for each cardiac cycle.

Subject and image groups and data processing

Two orders for the coronary wall imaging (right first and left first) were equally assigned to the 70 subjects. For the right first approach, we first performed coronary wall MRI on right coronary artery first in 35 subjects. For the left first approach, we acquired coronary images of the left coronary arteries first. The information from the participant MRI is shown in Table 1.

Image group 1 contains right coronary segments (RCA 1, RCA 2 and RCA 3 from the right first subjects) and left coronary segments (LM, LAD1, LAD 2 and LAD 3 from the left first subjects). Image group 2 contains right coronary segments from left first subjects and left coronary segments from right first subjects. See Figure 1 for the image grouping schemes.

Breathing frequency and HR were measured before the scans were initiated. The latency time (defined as the time between the start of the scan and the beginning of individual coronary segment imaging), drift in the position of the NAV (absolute discrepancy between the lowest level and the highest level of the NAV), scan efficiency (defined as the percentage of accepted ECG triggers among the available ECG triggers) and HR variations (defined as the maximum HR variations in the scan) were recorded on the MRI scanner for each coronary wall acquisition.

Coronary wall images were transferred to a SIEMENS workstation (Leonardo) for semi-automatic analysis. All images were reviewed by 1 author (KL, reader #1 has 5 years of experience in cardiovascular imaging) and were graded using a modified three-point system, based on the following criteria^{9,10}: 1) vessel (lumen) not visible or not eligible for analysis; 2) good image quality, eligible for analysis, and vessel (lumen) may have minor signal loss or image artifacts; and 3) excellent image quality and vessel (lumen) is observed continuously with minor signal loss. Coronary images with a score of "2" or "3" were considered as having "good" image quality and were eligible for analytical interpretation. Images with a score of "1" were considered as having "poor" image quality.

Reader #2 (YL, with 8 years of experience in clinical radiology) independently reviewed and ranked the coronary wall images for all participants to test the inter-observer agreement. Reader #1 ranked those images at least 1 month after the first review to test the intra-observer variation.

Statistical methods

The measurements are expressed as the mean $\pm$ one standard deviation (SD). All statistical processing was performed with SPSS software (SPSS Inc., Version 13.0, Chicago, IL, USA). Statistical significance was set at a two-tailed p -value < 0.05 . Chi-square tests were used to test the components of the subject groups. Latency periods, HR variations, drift in the position of the NAV, scan efficiency and image quality of groups 1 and 2 were compared using t tests and Mann-Whitney U tests. The Pearson's correlation coefficient (r) and Spearman's rank correlation coefficient (ρ) were used to investigate the relationships among the various factors. The Cohen's coefficient (κ) was applied to measure the intra-observer agreement (for reader #1) and inter-observer agreement (between reader #1 and #2) of the image ranking.

Results

No participants asked to terminate the examination during the MRI scan acquisition. All 70 coronary wall examinations were completed and resulted in 490 coronary segments for analysis.

Image group 1 ($n = 245$) had more "good" images than group 2 (62% [152 of 245] vs. 45% [111 of 245], $p < 0.001$). Image group 1 had a higher average image score (1.66 ± 0.55 vs. 1.46 ± 0.51 , $p < 0.001$), shorter latency time (32.04 ± 4.24 minutes vs. 44.22 ± 5.57 minutes, $p < 0.001$), lower drift of the location of the NAV (1.90 ± 1.27 mm vs. 2.61 ± 1.71 mm, $p < 0.001$) and higher scan efficiency ($32.7 \pm 7.6\%$ vs. $29.9 \pm 7.9\%$, $p < 0.001$) than group 2 ($n = 245$). There was no significant difference in the HR variations between group 1 and 2 (0.96 ± 0.82 beats/minute vs. 1.05 ± 0.89 beats/minute, $p = 0.17$). See Table 2 for comparisons between two image groups.

For all coronary images, the length of the latency time was moderately but significantly related to the image scores ($\rho = -0.467$, $p < 0.001$), the drift in the location of the NAV ($r = 0.489$, $p < 0.001$) and the scan efficiency ($r = -0.496$, $p < 0.001$). The image scores are also correlated with the drift of the location of the NAV ($\rho = -0.621$, $p < 0.001$) and scan efficiency ($\rho = 0.558$, $p < 0.001$).

For the image quality ranking, good intra-observer ($\kappa = 0.862$, $p < 0.001$) and inter-observer ($\kappa = 0.775$, $p < 0.001$) agreement were found for all 490 coronary segments.

The effects of the latency periods on the coronary wall MRI image quality are shown in Figure 2 (a right first case) and Figure 3 (a left first case).

Discussion

In the present study, our data show the relationship between a long latency time and inferior image quality in older adults. A higher drift of the NAV and lower scan efficiency during the coronary wall MRI were found to concurrently appear with a long latency time.

Since optimal MRI images are essential for the clinical diagnosis and studies, QM programs have been widely used to ensure the quality of care¹¹. However, current QM protocols/projects mainly monitor the performance of MRI facilities¹². Free-breathing coronary MRI is a time-consuming examination that requires examinees to spend long periods of time inside the scanner. In addition, coronary wall MRI is very sensitive to motion due to its small target area. Studies have shown that the overall interpretability rate of black-blood coronary wall MRI varies from 30% to 60% in general subjects^{6,7,13,14}. However, most studies only considered technical and physiological indices when the researchers built coronary wall MRI protocols. A long latency period was generally ignored because it seemed like a "non-technical" factor. Efforts to improve coronary wall MRI quality were concentrated on hardware and software that would shorten scan times and overcome cardiac motion effects¹⁵. In the present study, we quantified the role that latency times have on coronary wall MRI quality. For the first time, our results have verified the "presumed

feeling" that what has been considered a "non-technical" element of MRI scanning can have a significant impact on quality management for coronary MRI examinations.

Currently, no unique time threshold exists for individual clinical MRI scans. In fact, tolerance of MRI may vary among subjects of different ages and with different familiarity with the examination^{16,17}. With questionnaire surveys after MRI scans, previous studies showed that a long time (30 – 60 min) clinical MRI appears to be acceptable for most older and young subjects^{18–20}. However, "doable" does not mean "well done". Although none of the participants in this study asked to prematurely stop the scans because of significant discomfort, we observed the accumulated effects that longer latency times had on subjects who appeared tolerant of the scan process. We also detected meaningful changes in the technical and physiological statuses as the latency times increased. A long latency period was usually accompanied by higher drift in the location of the NAV and lower scan efficiency, both of which have been shown to reduce image quality in coronary wall MRI⁵. The impact of the latency time on predictors of image quality suggests that subtle variations on breathing modes are responsible for reduced image quality when latency times increase. The discovery of those variations may explain the impact of latency periods on coronary wall MRI quality and prompt further clinical solutions to counter with that impact.

In considering our results, we believe there may be a number of ways to compensate for the impacts that long latency periods have on coronary wall MRI quality. Shortening latency period times may directly improve image quality. A special imaging sequence that ensures coronary wall MRI is performed early might benefit the coronary image quality, especially when using cardiovascular MRI protocols that require multiple tasks/measurements. Additionally, technical advances in cardiovascular/coronary MRI that lead to shorter scan times will not only immediately improve the image quality but also decrease the latency time for subsequent imaging procedures and indirectly increase the image quality of subsequent coronary MRI. Suppressing irregular breathing modes may also be an alternative for offsetting the negative effects a long latency period has on coronary wall MRI quality²¹.

Our study has some limitations. First, we did not analyze all physiological conditions. According to the study design, coronary wall images were assigned to two image groups for comparison. We therefore only compared two variations affiliated with individual image acquisitions, the HR variations and respiratory motions. Other unintended body motions, such as chest movement, can be detected by measuring the drift of the NAV location. To highlight the effects of longer latency times, we only included older subjects because they tend to have slower HRs, and uncontrolled cardiac motion alone can destroy coronary wall MRI. Second, we did not take into account the effects of quantitative measurements affiliated with visual coronary walls, such as the signal to noise ratio (SNR), contrast to noise ratio (CNR) or coronary wall thickness, on the image quality. We believe that the indices acquired from those poor images are inaccurate. Third, we did not discriminate between the image quality of various vessel segments on different coronary branches due to the small sample size. Our previous MRI studies did not show significant differences in the image quality of different coronary branches in the MRI^{5,13}. Most importantly, the components of the coronary wall segments in the two image groups are the same for the present study. Fourth, we only evaluated the influence of latency periods in free-breathing

coronary wall MRI. Although similar results are expected in other cardiovascular/coronary MRI applications, further study is needed using different imaging techniques.

In conclusion, long latency period has a significantly negative impact on the image quality of coronary wall MRI. Effective control of latency time is expected to facilitate optimization of coronary MRI protocols in clinical studies.

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Figure 1.
The analyzed image groups

Figure 2.

An 84-year-old male with a 20-year history of HTN. His heart rate was 60 beats/minute. His body weight was 68.9 kg. His breathing frequency was 15 breaths/minute.

a The image quality of this patient's RCA1 (right first) scan was considered a "3". The latency time for imaging this coronary segment was 26 minutes. The location of the NAV was kept at 131 mm during the scan. The overall scan efficiency was 37%. The HR variation was 0 beats/minute.

b The image quality of this patient's LAD1 scan was considered a "2". The latency time for imaging this coronary segment was 39 minutes. The location of the NAV shifted from 132 mm to 131 mm. The drift of the NAV location was 1 mm. The overall scan efficiency decreased to 34%. The HR variation was 1 beat/minute.

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Figure 3.

A 71-year-old male with a 10-year history of DM. His heart rate was 54 beats/minute. His body weight was 70.5 kg. His breathing frequency was 14 breaths/minute.

a The image quality of this patient's LAD1 (left first) scan was considered a "3". The latency time for imaging this coronary segment was 30 minutes. The location of the NAV remained at 134 mm during the scan. The overall scan efficiency was 42%. The HR variation was 1 beat/minute.

b The image quality of this patient's RCA1 scan was considered a "2". The latency time for imaging this coronary segment was 42 minutes. The location of the NAV changed from 133 mm to 135 mm. The drift of the NAV location was 2 mm. The overall scan efficiency decreased to 35%. The HR variation was 1 beat/minute.

Table 1

Clinical information of two subject groups

	Right first (n = 35)	Left first (n = 35)	p value
Age (years)	72.7 ± 4.8	71.6 ± 4.1	0.275
Male (%)	18 (51.4)	20 (57.1)	0.631
Body weight (Kg)	70.9 ± 10.0	72.8 ± 9.9	0.424
HR (beats/minute)	57.9 ± 4.9	57.4 ± 4.7	0.711
Breathing frequency (breathing/minute)	15.11	15.60	0.329
HTN (%)	16 (45.7)	17 (48.6)	0.811
DM (%)	9 (25.7)	11 (31.4)	0.597

Table 2

Comparisons of two image groups

	Group 1 (n = 245)	Group 2 (n = 245)	p value
Good images (%)	152 (62.0)	111 (45.3)	< 0.001
Image scores			
Latency time (minutes)	32.04	44.22	< 0.001
Drift of the NAV (mm)	1.90 ± 1.27	2.61 ± 1.71	< 0.001
Scan efficiency (%)	32.7 ± 7.6	29.9 ± 7.9	< 0.001
HR variations	0.96 ± 0.82	1.06 ± 0.89	0.17