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The compensation for asynchronous cardiac quiescence in coronary wall MR imaging

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Abstract

The aim of the present study was to assess the incremental benefit of compensating asynchronous cardiac quiescence in coronary wall MR imaging. With the approval of IRB, black-blood coronary wall MR imaging was performed on 30 older subjects (90 coronary wall segments). For round 1 coronary wall MR imaging, acquisition windows were traditionally set within rest period 4-chamber. Totally 51 of 90 images were ranked as "good" images and resulted in an interpretability rate of 57%. Then, an additional cine-MR was centered at coronary segments to obtain rest period cross-sectional. The rest period overlap (the intersection between rest period 4-chamber and rest period cross-sectional) was measured for each coronary segments. The "good" images had a longer rest period overlap and higher acquisition coincidence rate (the percentage of acquisition window covered by the rest period overlap) than "poor" images. Coronary wall rescans (round 2) were completed at 39 coronary segments that were judged as having "poor" images in round 1 scans. The acquisition windows was set within the rest period overlap. For the round 2 images, 17 of 39 (44%) coronary segments was ranked as "good" images. The overall interpretability rate (68 of 90, 76%) was significantly higher than that of the round 1 images alone. Our data demonstrated that asynchronous cardiac quiescence adversely affects the performance of coronary wall MR imaging. Individualizing acquisition windows based on multi-plane cine-MR imaging helps to compensate for this motion discrepancy and to improve image quality.

Keywords

Coronary wall MR imaging; Asynchronous quiescence; Compensation

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Conflict of interest:

No conflict of interest to disclose

Introduction

Coronary artery disease (CAD) is prevalent in the older population [1]. The primary manifestation of CAD is the narrowing of coronary lumens and remodeled coronary walls with the contributions of various cardiovascular risk factors [2, 3]. Traditional methods for observing the coronary wall and lumen require invasive procedures or X-ray exposure. In many recent epidemiological studies, black-blood coronary wall magnetic resonance (MR) imaging has been adopted as a noninvasive examination for the assessment of the progression of subclinical CAD in asymptomatic elderly [4–6]. However, coronary motion has become a significant physiological and technical barrier for coronary wall MR imaging [7]. As a result, the overall interpretability rate of black-blood coronary wall MR imaging for quantitative analysis remains approximately 30% – 60% in general subjects [8, 9, 5, 7]. Such an unfavorable productivity seriously impedes the application of this promising imaging method in clinical studies.

Continuous heart beating is one of the primary sources of coronary motion. Currently, the commonly used technical strategy for minimizing the effects of cardiac motion is to acquire pieces of imaging data (k-space lines) during short "cardiac quiescent" periods over multiple cardiac cycles according to electrocardiogram (ECG) triggering. However, the "rest period" within a single heart beat is typically identified using a set of two-dimensional (2D) cardiac cine images obtained in the "4-chamber" view, even for multi-plane coronary MR imaging [5, 4, 8, 9]. A 2D imaging technique is unable to fully depict the coronary motion in three orthogonal directions (all components of the vector). There may be undetected local motion during the "rest period" displayed on a 2D cardiac cine for each coronary segment. Indeed, the coronary artery deforms in a three-dimensional (3D) space and the entire coronary tree may not deform synchronically. We therefore hypothesized that cine-MR imaging at the target coronary segment would be helpful for detecting "hidden" cardiac motion and further refining the "rest period" on a "per-segment" basis. The accurate timing of data collection is therefore expected to improve the image quality of the coronary artery. With an existing older cohort with low heart rates, the aim of the present study was to assess the incremental benefit of compensating asynchronous cardiac rest periods on coronary wall MR imaging using cine-MR imaging at two different imaging planes (4-chamber and cross-sectional).

Materials and methods

Patient study

This study was compliant with HIPAA regulations. Following the approval of the institutional review board (IRB), 30 asymptomatic participants of the CHICAGO HEALTHY AGING LOW RISK MR ANGIOGRAPHY (CHARISMA) study, including 16 male subjects (mean age 71.4 ± 6.1 years old, range 66 – 84 years old; body weight 74.9 ± 6.8 kg; heart rate 57.5 ± 5.9 beats/minute, range 48 – 65 beats/minute) and 14 female subjects (mean age 70.9 ± 3.6 years old, range 66 – 84 years old; body weight 62.8 ± 9.1 kg; heart rate 56.9 ± 4.6 beats/minute, range 52 – 63 beats/minute) were recruited for cardiac MR scans. Written informed consent was provided by all the participants. Participants with existing diabetes mellitus (DM) and hypertension (HTN) were identified based on self-reporting and medical records. The information for the participants is shown in table 1.

The general inclusion criterion for the CHARISMA cohort was asymptomatic subjects (66 – 85 years old) without a documented history of cardiovascular diseases. The exclusion criteria for the present study were as follows: contradictions for MR imaging; heart rate > 65 beats/minute; breathing frequency > 24 breaths/minute; and renal dysfunction (defined as an estimated glomerular filtration rate [eGFR] < 60 mL/minute/1.73 m²).

Imaging protocols

All scans were performed on a clinical 1.5 T MR scanner (MAGNETOM, Espree, SIEMENS) by two certified clinical MR technologists. For each participant, a 3-plane fast-localization sequence was run first for anatomic orientation for the entire scan. The 2-chamber, 4-chamber, and short-axis views were localized for coronary imaging. Then, 4-chamber cardiac moving images of the heart were acquired with a segmented 2D steady-state free precession (SSFP) sequence to determine the rest periods of cardiac motion in the cardiac cycles. The imaging parameters included TR/TE = 2.8/1.1 ms, flip angle = 65° and spatial resolution = $2.1 \times 2.1 \times 4 \text{ mm}^3$. A total of 22 reconstructed cardiac phases were acquired with retrospective gating during a breath hold. In-plane coronary artery motion and velocity were calculated on cine images by interactive identifying the displacement of left and right coronary arteries (with in-plane x and y coordinates) through sequential phases [10]. Rest period_{4-chamber} was defined as the duration when the coronary arteries moved slower than 4 cm/second (in-plane) in mid-diastole [10]. Whole-heart coronary MR angiography was acquired with a navigator (NAV) -gated, ECG-triggered, fat-saturated, T2-prepared, segmented 3D SSFP sequence. The imaging parameters included the following: field of view (FOV) = $320 \times 320 \text{ mm}^2$; TR/TE = 3.7/1.7 ms; flip angle = 90-degree; k-space lines acquired per heartbeat = 17 – 35; readout bandwidth = 870 Hz/pixel; and parallel acquisition factor = 2. The in-plane spatial resolution was $1.1 \times 1.1 \text{ mm}^2$. The slice thickness was 0.7 mm. 3D multiplanar reformations (MPRs) were performed on MR angiography images to localize the left main (LM) artery, proximal left anterior descending (LAD) artery, and right coronary artery (RCA). Cross-sectional black-blood images of the proximal portions of the coronary arteries were acquired using an NAV-gated, ECG-triggered, double inversion recovery (DIR)-prepared, 2D turbo spin echo (TSE) sequence. Being perpendicular to the long axis of the vessel, at 5 mm from the origins of the RCA, the LM and the LAD, three cross-sectional slices were acquired based on anatomical landmarks for quantitative analysis. The imaging parameters included the following: TR = 800 ms; TE = 33 ms; 11 k-space lines per cardiac cycle (fixed for all coronary wall MR scans in the present study); bandwidth = 305 Hz/pixel; field of view (FOV) = $420 \times 420 \text{ mm}^2$; matrix = 416×416 ; and slice thickness = 4.0 mm (the same as the cardiac cine). A spectral-selective adiabatic inversion recovery (SPAIR) pulse was applied to improve the tissue contrast between the coronary wall and epicardial fat by suppressing fat signals. For all coronary segments, the duration of data acquisition (93 msec) was routinely set at the middle of rest period_{4-chamber}. After the round 1 imaging, an extra cardiac cine-MR imaging was performed and centered at the portions of all coronary segments with the same imaging parameters as the 4-chamber views. Rest period_{cross-sectional} was also defined as the duration in mid-diastole when the target coronary segments moved slowly (in-plane velocity < 4 cm/sec) [10]. Rest period_{overlap} was defined as the timing intersection of rest period_{4-chamber} and rest period_{cross-sectional}. The round 2 coronary wall MR imaging was performed 15 minutes after the round 1 imaging at the same coronary positions only if the image quality of the coronary wall MR image was judged as "poor" by reader #1 (KL, 5 years of experience in cardiovascular imaging) at the scanner. The same imaging parameters were used, with the exception of the acquisition windows, which were put in "rest period_{overlap}".

Image evaluation and data processing

All images were reviewed by reviewer #1 during the scan and were graded using a modified three-point system, based on the following criteria [4, 11]: 1) vessel (lumen) not visible or not eligible for analysis; 2) high image quality, eligible for analysis; the vessel (lumen) may have minor signal loss or image artifacts; and 3) excellent image quality, the vessel (lumen) is observed continuously with minor signal loss. Coronary images with a score of "2" or "3" were considered to have "good" image quality and to be eligible for quantitative analysis, whereas a score of "1" was assigned to "poor" image quality. The "coincidence rate" was

defined as "the overlap between the acquisition window and rest period_{overlap}" / "93 msec" $\times 100\%$. The interpretability rate of images was defined as "the number of good images" / "the number of imaged coronary segments" $\times 100\%$.

Agreement tests for image ranking

Coronary wall MR images were transferred to a SIEMENS imaging workstation (Leonardo) for semi-automatic analysis. Using the same criteria, two readers (#1 and #2, with 8 years of experience in clinical radiology) independently ranked coronary wall images and measured the length of cardiac rest periods of 10 randomly chosen participants to test the inter-observer agreement. Reader #1 repeated the analysis on the same participants 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). On a per-segment basis, rest period_{4-chamber}, rest period_{cross-sectional}, rest period_{overlap} and the coincidence rate were compared between "good" images and "poor" images using student *t*-tests. The interpretability rates of coronary images between two rounds of coronary wall MR scans were compared with Chi-squared tests. Bland-Altman plots were used to investigate the intra- and inter-observer agreements of rest period measurements. Spearman's rho was applied to measure intra- and inter-observer agreements of image quality scoring. 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 .

Results

In total, 30 coronary wall MR scans were completed. For the round 1 coronary wall MR scans, 51 of 90 (57%) coronary wall images acquired from 25 participants were considered as having high image quality. The start time and length of the rest periods varied greatly among individual coronary segments. There were significant differences in the length of rest period_{overlap} (152.1 ± 29.5 msec vs. 121.3 ± 25.7 msec, $P < 0.001$) and the coincidence rates for the round 1 scans ($93\% \pm 11\%$ vs. $76\% \pm 20\%$, $P < 0.001$) between "good" images and "poor" images (figure 1). No significant differences were found in the length of rest period_{4-chamber} (182.2 ± 46.7 msec vs. 177.2 ± 50.1 msec, $P = 0.628$) or rest period_{cross-sectional} (181.6 ± 44.2 msec vs. 174.7 ± 53.2 msec, $P = 0.496$) between the two image groups, respectively. The round 2 coronary wall MR imaging was repeated on 39 coronary wall segments (from 23 participants) for which the image quality was scored "1" for the round 1 images; 17 (44%) of the 39 segments (from 15 participants) were considered to have high image quality at this time. There was no significant difference in the interpretability rate between the round 1 and round 2 images (57% vs. 44% , $P = 0.172$). However, the overall interpretability rate of coronary wall images (68/90, counting good images acquired from both rounds 1 and 2) was significantly higher than that of the round 1 images alone (76% vs. 57% , $P = 0.007$). The data are summarized in table 2 and 3. A typical case with a successful compensation for the asynchronous cardiac motions in the LAD is shown in figure 2.

For the two rounds of coronary wall MR imaging, there was good intra-observer agreement (Spearman's rho = 0.942, $P < 0.001$) and inter-observer agreement (Spearman's rho = 0.834, $P < 0.001$) in the coronary wall scores of 41 coronary wall images from 10 randomly chosen participants. Bland-Altman plots also indicated low intra- and inter-observer variances in the rest period measurements of those cases (figure 3).

Discussion

In the present study, we observed asynchronous stillness of coronary segments in older adults. The discrepancy between "rest periods" identified on 4-chamber views and cross-sectional views is adversely related to the image quality of coronary wall MR imaging. Compared to the traditional imaging protocol, adjusting the acquisition window according to moving cine-MR images acquired on two imaging planes may significantly improve the image quality of black-blood coronary wall MR imaging.

The motion of the heart is not linear or homogenous. Minimizing the effects of the motion of the coronary artery on image quality is considered technically critical in coronary MR imaging. Many advances in imaging techniques, including motion correction algorithms and section tracking schemes, have been developed to address clinical needs for high-quality coronary wall images. However, variations in the subject-specific "rest period" under general physical conditions and the implications for coronary imaging have also been described. Currently, using ECG gating to individualize an acquisition window on a "per-patient" basis is a convenient strategy for dealing with cardiac motion in coronary wall MR imaging. The timing of the data acquisition could be determined before the scan using 2D MR acquisition [12]. However, an obvious drawback of this scheme is that the coronary branches are treated as a whole unit. Indeed, the contraction and filling patterns of the chambers and vessels affects the movements of individual coronary parts dissimilarly. Furthermore, the behavior of coronary motion is also affected by the local environment, such as movements of the diaphragm and chest wall. Using traditional X-ray angiography, Wang et al. measured the length of the rest period of cardiac motion within the cardiac cycle on two imaging planes. The authors found that there were substantial variations in the lengths of the cardiac rest periods in different parts of the coronary tree among individual patients [13]. Additionally, using biplane X-ray angiography for 15 patients diagnosed with CAD, Kevin et al. identified a "rest period" for all major coronary branches with an average length of 187 msec at mid-diastole. Hofman et al. quantified different magnitudes of in-plane displacement of the coronary arteries under normal physiological conditions during the cardiac cycle using MR imaging [14]. Shechter et al. also showed different "rest periods" in various parts of the coronary tree [15].

Unlike existing protocols of coronary wall MR imaging, we added an extra cardiac cine in a cross-sectional view of the coronary segments and unveiled the "hidden" component of the motion vector, which could have been missed by using the traditional protocol of coronary wall MR imaging. The severity of the nonsimultaneous cardiac motion, represented as the length of rest period _{overlap} and the acquisition coincidence rate, is quantitatively related to the ranking of image quality. Replacing rest period _{4-chamber} with rest period _{overlap}, we technically compensated the timing disparities of the coronary motion and increased the coronary image quality of the current clinical MR hardware platform. To the best of our knowledge, we are the first group to describe the "rest period" at the "per-segment" level based on two different 2D imaging planes. In addition to black-blood coronary wall MR imaging, accurate timing may also have intrinsic significance for other quantitative MR imaging applications in clinical research, including cardiovascular flow measurement and MR angiography.

This study has some limitations. First, we only studied the "rest period" in mid-diastole, although there is another cardiac motion-free duration located in "systole" that can also be utilized for coronary MR imaging [11, 16, 12]. However, the "rest period" in mid-diastole is more commonly used for clinical imaging, and we were unable to compare images acquired at systole in our participants due to the limited scan time. Second, we only repeated imaging on 39 coronary segments whose round 1 MR images were ranked "1". We therefore cannot

comprehensively assess the added value of resetting acquisition windows on image acquisitions ranked "2" or "3". Nevertheless, the increase in the overall interpretability rate suggests the net gain of using a more accurate acquisition window. Third, it is worth noting that the images of 22 coronary segments were still ranked "1" on the round 2 MR images even after we adjusted the acquisition windows. We acknowledged that many physiological factors, such as respiratory motion, heart rate variation, body weight and voluntary motion, may independently affect image scoring [17–19]. We controlled for some important physical conditions, including a low heart rate, to avoid the bias on the comparisons, although we were unable to adjust all physiological factors in this pilot study due to the small sample size.

In summary, our data showed that asynchronous cardiac quiescence adversely affects the performance of coronary wall MR imaging. Individualizing acquisition windows based on multi-plane cine-MR imaging helps to compensate this motion discrepancy and to improve image quality.

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Figure 1.

There were significant differences in the length of rest period overlap (152.1 ± 29.5 msec vs. 121.3 ± 25.7 msec, $P < 0.001$) and the coincidence rates for the round 1 scans ($93\% \pm 11\%$ vs. $76\% \pm 20\%$, $P < 0.001$) between "good" images and "poor" images.

Figure 2.

A 70-year-old male with a 10-year history of HTN (controlled with medications). His heart rate was 61 beats/minute. His body weight was 76 Kg.

a Four-chamber cine showed that the rest period for the left coronary artery (red arrow) started at 589 msec and ended at 794 msec. The length of rest period _{4-chamber} was 205 msec.

b For the round 1 coronary wall MR scans, we obtained an image of the LM that was scored "2" (red arrow) when the acquisition window (93 msec) was set at 645 msec to 738 msec (in the middle of rest period _{4-chamber}).

c When the same acquisition window (from 645 msec to 738 msec) was used for imaging the LAD, we obtained an image that was scored "1" (red arrow).

d Cross-sectional cine-MR imaging was then performed at the position of the LM (red arrow). The rest period_{cross-sectional} for the target LM segment artery started at 626 msec and ended at 810 msec. The rest period_{overlap} (168 msec) started at 626 msec and ended at 794 msec. The acquisition coincidence rate was 100% (the entire pre-set acquisition window was covered by rest period_{overlap}).

e Cross-sectional cine-MR imaging was run at the position of the LAD (red arrow). The rest period_{cross-sectional} for the target LAD segment artery started at 665 msec and ended at 833 msec. The rest period_{overlap} (129 msec) started at 665 msec and ended at 794 msec. The acquisition coincidence rate was 79% (73 msec of the pre-set acquisition window was covered by rest period_{overlap}).

f In the round 2 coronary wall MR scans, we imaged the LAD with an adjusted acquisition window (from 680 msec to 773 msec), which was fully covered by rest period_{overlap}. The image quality was scored "2" at this time (red arrow).

Figure 3.
 Intra- and inter-observer agreements for the measurements of rest periods on 10 randomly chosen participants.
 a Low intra-observer variation on rest period measurements.
 b Low inter-observer variation on rest period measurements.

Table 1

Study participant information (N = 30)

Age (years)	71.1 $\pm$ 3.8
Male (%)	16 (53)
Height (cm)	168.5 $\pm$ 8.7
Bodyweight (Kg)	69.2 $\pm$ 9.9
Heart rates (beats/minute)	57.3 $\pm$ 5.2
HTN (%)	17 (57)
DM (%)	6 (20)

Table 2

The results of round 1 coronary wall MR imaging			
Thirty participants for coronary wall MR scan (N = 90)			
	Good images	Poor images	P value
Successful MR scans (Interpretability rate, %)	51 (57)	39 (43)	
Rest period _{4-chamber} (msec)	182.2 ± 46.7	177.2 ± 50.1	= 0.628
Rest period _{cross-sectional} (msec)	181.6 ± 44.2	174.7 ± 53.2	= 0.496
Rest period _{overlap} (msec)	152.1 ± 29.5	121.3 ± 25.7	< 0.001
Coincidence rates (%)	93 ± 11	76 ± 20	< 0.001

The results from round 2 coronary wall MR imaging		
Twenty-three participants for coronary wall re-scan (N = 39)		
	Good images	Poor images
Successful re-scans (Interpretability rate, %)	17 (44)	22 (56)
Over successful MR scans (Interpretability rate, %)	68 (76)	22 (24)