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Prospective Heart Tracking for Whole-heart Magnetic Resonance Angiography

Mehdi H. Moghari^{1,2}, Tal Geva^{1,2}, and Andrew J. Powell^{1,2}

¹Department of Cardiology, Boston Children's Hospital, Boston, MA, USA

²Department of Pediatrics, Harvard Medical School, Boston, MA, USA

Abstract

Purpose—To develop a prospective respiratory-gating technique (Heart-NAV) for use with contrast-enhanced 3D inversion recovery (IR) whole-heart magnetic resonance angiography (MRA) acquisitions that directly tracks heart motion without creating image inflow artifact.

Methods—With Heart-NAV, 1 of the startup pulses for the whole-heart steady-state free precession MRA sequence is used to collect the centerline of k-space, and its 1-dimensional reconstruction is fed into the standard diaphragm-navigator (NAV) signal analysis process to prospectively gate and track respiratory-induced heart displacement. Ten healthy volunteers underwent non-contrast whole-heart MRA acquisitions using the conventional diaphragm-NAV and Heart-NAV with 5 and 10 mm acceptance windows in a 1.5T scanner. Five patients underwent contrast-enhanced IR whole-heart MRA using a diaphragm-NAV and Heart-NAV with a 5 mm acceptance window.

Results—For non-contrast whole-heart MRA with both the 5 and 10 mm acceptance windows, Heart-NAV yielded coronary artery vessel sharpness and subjective visual scores that were not significantly different than those using a conventional diaphragm-NAV. Scan time for Heart-NAV was 10% shorter ($p < 0.05$). In patients undergoing contrast-enhanced IR whole-heart MRA, inflow artifact was seen with the diaphragm-NAV but not with Heart-NAV.

Conclusion—Compared to a conventional diaphragm-NAV, Heart-NAV achieves similar image quality in a slightly shorter scan time and eliminates inflow artifact.

Keywords

Whole-heart angiography; respiratory motion; self-navigator; prospective motion correction

INTRODUCTION

Electrocardiogram (ECG) and respiratory-gated 3-dimensional (3D) magnetic resonance whole-heart angiography (MRA) acquisitions of the chest provide high-resolution anatomic datasets allowing for a comprehensive evaluation of intracardiac, coronary, and vascular abnormalities (1). ECG-gating is needed to minimize cardiac motion artifact and works by

confining image data collection to only about 10% of the cardiac cycle, when motion is at its minimum. Respiratory-gating is needed to compensate for breathing-related motion as the high-spatial resolution, extensive anatomic coverage, and ECG-gating prolong scan time well beyond the interval a patient can hold their breath. In the typical commercially available technique, a respiratory navigator beam (NAV) is used to track the position of the right hemi-diaphragm, or more specifically, the liver-lung interface, and only accept data acquired during end-expiration (2). The image quality of ECG and respiratory NAV-gated MRA acquisitions can be further improved by intravenous administration of a gadolinium-based contrast agent and the application of a non-selective inversion recovery (IR) pulse timed to null the myocardial signal (3–5). This approach increases the signal intensity of blood as well as the contrast between blood and myocardium. A variation in this technique is also used for 3D myocardial late gadolinium enhancement imaging (6).

There are, however, at least 2 drawbacks to using a diaphragm-NAV with contrast-enhanced IR whole-heart MRA sequences. The first is NAV-related image artifact. The IR pulse intended to null the myocardium also reduces the signal in the liver and, thus, hinders diaphragm (liver-lung interface) tracking as the lung tissue also has low signal. To counteract this effect, a slice selective inversion pulse, also termed a “NAV-restore pulse,” is typically added to selectively restore the signal in the liver. The NAV-restore pulse, however, excites the blood flowing from systemic and pulmonary veins into the heart creating a bright inflow artifact that hinders image interpretation (7,8). The second drawback to using a diaphragm NAV is that right hemi-diaphragm motion does not always accurately reflect respiratory-induced heart motion. In particular, the scaling (tracking) factor between diaphragm movement and heart movement varies among patients, and there is a temporal delay and hysteresis (9,10).

To address these shortcomings, we developed an alternative method for prospective respiratory-gating (Heart-NAV) for use with whole-heart MRA acquisitions that directly tracks respiratory-induced heart motion without creating image artifact. With Heart-NAV, 1 of the startup pulses for the whole-heart MRA sequence is used to collect the centerline of k-space, and its 1-dimensional reconstruction is fed into the standard respiratory NAV signal analysis and gating process. To assess the efficacy of respiratory motion compensation, non-contrast ECG-gated whole-heart MRA acquisitions with Heart-NAV and the conventional diaphragm-NAV were compared in healthy volunteers. To evaluate image artifact, contrast-enhanced ECG-gated IR whole-heart MRA acquisitions with Heart-NAV and a diaphragm-NAV were compared in patients.

METHODS

Heart-NAV Technique for Non-contrast Whole-heart MRA

Schematic diagrams of the non-contrast whole-heart MRA sequence with a conventional diaphragm-NAV and Heart-NAV are shown in Figure 1(A, B). Both use a 3D steady-state free precession (SSFP) sequence to acquire whole-heart MRA data in a sagittal orientation with frequency encoding in the superior-inferior direction. To minimize cardiac motion artifacts, the data is divided into multiple segments, each of which is acquired during the quiescent period of the cardiac cycle set by the trigger delay and acquisition window

duration. For the diaphragm-NAV sequence, 5 startup pulses are employed to approximate the steady state for the subsequent MRA data acquisition. Fold-over suppression is achieved by applying 2 parallel saturation bands in the phase-encode direction to reduce the signal of tissues outside the field of view. T2-preparation and fat-suppression pre-pulses precede the fold-over suppression pulse to enhance the contrast between the blood and myocardium and to minimize the signal from fat. A diaphragm-NAV acquisition is performed before fat-suppression and after the T2-preparation pre-pulses to assess the position of the right hemidiaphragm and to track the heart by adjusting the imaging volume position. In the proposed Heart-NAV technique, however, a diaphragm-NAV is not performed. Instead, the analog-to-digital converter of the diaphragm-NAV is modified to measure the gradient echo signal generated from the first startup pulse in the SSFP whole-heart MRA sequence. The phase and slice encode gradients of this startup pulse are set to 0 to measure the centerline of k-space along the superior-inferior direction. Using the same processing pathway as the diaphragm-NAV, the data from the echo is collected and transformed from the Fourier domain to the image domain, a process that takes approximately 5 ms. This image data represents the 1-dimensional projection line of the whole-heart MRA imaging volume along the superior-inferior direction including the liver, heart, chest wall, and spine. The image data is processed and displayed using the same procedure as for a diaphragm-NAV including a cross-correlation analysis with the preceding Heart-NAV line to measure displacement in the superior-inferior direction and prospectively adjust the position of the imaging volume (Figure 2). Specifically, the first acquired projection line is set as a reference ($P_0(x)$), where P_0 represents the pixel intensity at position x along the superior-inferior direction. On the projection line, a region of interest or kernel is defined to include the projection of the heart ($K(x)$). The kernel location is based on the position of the conventional diaphragm-NAV during the prescription of the Heart-NAV sequence and has a fixed length (w) of 80 mm. The next acquired projection line $P_i(x)$ is overlaid on the kernel ($K(x)$) and shifted Δx pixels to maximize the cross-correlation function (CC) as follows:

$$CC(\Delta x) = \frac{\sum_w (p_i(x - \Delta x) - \text{mean}(p_i(x - \Delta x))) \times (k(x) - \text{mean}(k(x)))}{\sqrt{\sum_w (p_i(x - \Delta x) - \text{mean}(p_i(x - \Delta x)))^2 \times \sum_w (k(x) - \text{mean}(k(x)))^2}}.$$

The value of Δx which maximized the cross-correlation ($CC(\Delta x)$) is then chosen as the respiratory-induced heart displacement at the i^{th} cardiac cycle and used for prospective gating and tracking. As with a diaphragm-NAV, whole-heart MRA data acquired when the NAV signal is outside the acceptance window is rejected and re-acquired (i.e., <100% data collection efficiency).

Heart-NAV Technique for Contrast-enhanced IR Whole-heart MRA

Schematic diagrams of the contrast-enhanced IR whole-heart MRA sequence with a conventional diaphragm-NAV and Heart-NAV are shown in Figure 1(C, D). As in the non-contrast technique, a 3D SSFP sequence is used to acquire whole-heart MRA data, and fold-over suppression and fat saturation pre-pulses are applied. However, rather than promoting myocardium-blood contrast by using a T2-preparation pulse, this is accomplished by administering an intravenous contrast agent to shorten the T1 and increase the signal of

blood and by performing a nonselective IR pulse timed to null the signal from the myocardium (3). Because the IR pulse also reduces the signal in the liver and thus would hinder diaphragm (liver-lung interface) tracking, a slice selective inversion (NAV-restore) pulse follows the nonselective IR pulse to restore the signal in the liver in the diaphragm-NAV sequence. However, the NAV restore pulse is not needed with the Heart-NAV sequence because it compensates for respiratory motion by tracking the 1-dimensional projection of whole-heart MRA imaging volume as described above.

Phantom Study

A phantom study was undertaken to assess the performance of Heart-NAV with respect to prospective motion estimation and correction of k-space lines. Using a Philips 1.5T Achieva scanner (Philips Medical Systems, Best, the Netherlands) and a 32-element receiver coil array, a high-resolution phantom was imaged with the non-contrast Heart-NAV whole-heart 3D SSFP MRA sequence with the following parameters: field of view $386 \text{ (SI)} \times 150 \text{ (AP)} \times 220 \text{ (RL)}$ mm, voxel size 1.5 mm^3 , flip angle 90° , echo time 2.4 ms, repetition time 4.7 ms, sensitivity encoding (SENSE) factor 2, NAV acceptance window 100 mm, and tracking factor 1. The same sequence was repeated but paused twice to displace the phantom along the superior-inferior direction by 20 mm and 10 mm, while the Heart-NAV data was used to prospectively estimate and correct the motion. Finally, to create a reference image, a static phantom was imaged using the non-contrast diaphragm-NAV whole-heart MRA sequence with the same imaging parameters.

Human Study

To investigate the ability of Heart-NAV to compensate for respiratory-induced heart motion and compare it to the conventional diaphragm-NAV, healthy volunteers were examined using the aforementioned scanner and receiver coil. In each subject, a high temporal resolution cine SSFP 4-chamber slice was acquired to identify the rest period of the heart in order to specify the trigger delay and shot duration. Then, 4 non-contrast whole-heart 3D SSFP MRA datasets were obtained: 1) diaphragm-NAV with a 5 mm acceptance window, 2) diaphragm-NAV with a 10 mm acceptance window, 3) Heart-NAV with a 5 mm acceptance window, and 4) Heart-NAV with a 10 mm acceptance window. Other parameters were as follows: field of view $386 \text{ (SI)} \times 230 \text{ (AP)} \times 120 \text{ (RL)}$ mm, voxel size 1.5 mm^3 reconstructed to 0.75 mm^3 , flip angle 90° , echo time 2.4 ms, repetition time 4.7 ms, bandwidth 542 Hz, SENSE factor 2, and NAV tracking factor 0.6. A tracking factor of 0.6 was used for both sequences in order to minimize differences between the techniques and account for the possibility that, in the absence of an intravascular contrast agent, moving signal from liver-heart interface may be superimposed on the signal from heart motion. Scan times were recorded.

To investigate the effectiveness of Heart-NAV in eliminating inflow artifact related to the NAV-restore pulse, patients with a clinical indication for contrast-enhanced IR whole-heart MRA were recruited. In each patient, both the diaphragm-NAV and Heart-NAV versions of the contrast-enhanced IR whole-heart MRA sequence were performed with otherwise identical imaging parameters. These acquisitions were performed 2–3 minutes after a bolus infusion of 0.03 mmol/kg of gadofosveset trisodium contrast. A Look-Locker sequence was performed before each acquisition to determine the inversion time to null the myocardial

signal. The Boston Children's Hospital Committee on Clinical Investigation approved this study, and written informed consent was obtained from the volunteers and patients.

Image Analysis

Both the diaphragm-NAV and Heart-NAV MRA images were reconstructed in-line, immediately following scan completion, using the standard scanner hardware. For the phantom study, image sharpness was objectively quantified by calculating entropy (11), where lower entropy indicates better sharpness. For the non-contrast MRA datasets in volunteers, visualization of the coronary arteries was used as an indicator of overall image quality because their small size and mobility make them challenging targets to image clearly, and there are standardized metrics for analysis. For objective assessment, the vessel sharpness of the right coronary artery (RCA), left anterior descending coronary artery (LAD), and left circumflex coronary artery (LCX) was measured using a validated software tool (Soap-Bubble) (12). For subjective assessment, images were independently evaluated by 2 experienced clinicians blinded to the imaging technique. Both graded each coronary artery using a 4-point scale (13): (1) poor or uninterpretable: coronary artery visible with markedly blurred borders, (2) fair: coronary artery visible with moderately blurred borders, (3) acceptable: coronary artery visible with mildly blurred borders, or (4) excellent: coronary artery visible with sharply defined borders. For the contrast-enhanced MRA datasets in patients, the presence of inflow artifact was evaluated by 2 clinicians blinded to the imaging technique.

Statistical Analysis

Descriptive statistics are reported as mean $\pm$ standard deviation. A two-tailed paired Student t-test was used to compare the vessel sharpness, and a non-parametric signed-rank test was used to compare the subjective scores. A p -value ≤ 0.05 was considered statistically significant.

RESULTS

Phantom Study

The results of the phantom study are shown in Supporting Figure S1. Images of the static phantom with a diaphragm-NAV and with Heart-NAV had a similar appearance and entropy-based sharpness score. When the phantom was moved 20 mm and then 10 mm in the superior-inferior direction during a Heart-NAV acquisition, displacement was accurately tracked. This information was used to prospectively adjust the imaging volume position and yielded an image with a similar appearance and entropy-based sharpness score as the static acquisitions.

Human Studies

Ten healthy volunteers (7 females; age 31 ± 6 years) underwent non-contrast whole-heart 3D MRA acquisitions and the acquisitions and image reconstructions were successfully completed. Representative reformatted images from 2 subjects are shown in Figure 3. The mean subjective visual scores, objective vessel sharpness measures, and scan time for all subjects are shown in Table 1. There was no significant difference in vessel sharpness or

visual score between the diaphragm-NAV and Heart-NAV images for all 3 coronary artery branches at both the 5 mm and 10 mm NAV acceptance window. The mean scan time for Heart-NAV was approximately 10% shorter than that for the diaphragm-NAV at both the 5 mm and 10 mm acceptance windows.

For the diaphragm-NAV images, vessel sharpness was significantly better with a 5 mm acceptance window than with a 10 mm window for the LCX; there was no difference for the RCA and LAD (LCX, $p=0.040$; RCA, $p=0.26$; LAD, $p=0.055$). The visual scores were significantly better with a 5 mm acceptance window for the all 3 coronary artery branches (RCA, $p=0.001$; LAD, $p=0.001$; LCX, $p=0.002$). Scan time was shorter with a 10 mm acceptance window ($p<0.001$).

For the Heart-NAV images, vessel sharpness was significantly better with a 5 mm acceptance window than a 10 mm window for RCA and LAD; there was no difference for the LCX (RCA, $p=0.003$; LAD, $p=0.034$; LCX, $p=0.18$). The visual scores were significantly better with a 5 mm acceptance window for all 3 coronary branches (RCA, $p=0.001$; LAD, $p=0.008$; LCX, $p=0.003$). Scan time was shorter with a 10 mm acceptance window ($p<0.001$).

Contrast-enhanced IR whole-heart MRA sequences were also successfully performed in 5 patients with congenital heart disease (3 males; age 0.3 to 6 years). Representative images are shown in Figure 4. A prominent inflow artifact was noted by both reviewers in all diaphragm-NAV acquisitions but not in the Heart-NAV acquisitions. The small sample size precluded a meaningful comparison of image quality and scan time.

DISCUSSION

We have developed a novel technique (Heart-NAV) to prospectively track heart position and correct for respiratory-induced motion during 3D whole-heart MRA sequences. In this approach, 1 of the startup pulses for the MRA sequence is used to collect the centerline of k-space, and its 1-dimensional reconstruction is fed into the standard respiratory NAV signal analysis and gating process. In a phantom study, Heart-NAV accurately tracked and corrected for motion along the superior-inferior direction to produce an image similar to that from a static phantom. When applied to healthy volunteers for non-contrast whole-heart MRA, Heart-NAV yielded coronary artery vessel sharpness and visual scores that were comparable to those using a conventional diaphragm-NAV. In patients undergoing contrast-enhanced IR whole-heart MRA, the inflow artifact obscuring the pulmonary and systemic veins apparent with the diaphragm-NAV was not seen with Heart-NAV.

Although Heart-NAV directly tracks heart position and has less temporal delay between the NAV and the MRA acquisitions, its image quality and sharpness scores were not superior to those using a diaphragm-NAV. This similarity may be related to a relatively low MRA spatial resolution which is insufficient to detect small improvements in image quality (10). Furthermore, the fidelity of Heart-NAV tracking may have been limited because the 1-dimensional sagittal projection of imaging volume (kernel) is not composed exclusively of signal from the heart. Rather, static regions, such as the spine, and moving regions, such as

the superior aspect of the liver, are superimposed on the heart signal. The superimposition of the moving liver signal may have also limited the improvement in gating efficiency and reduction in scan time expected with tracking the heart versus the diaphragm because the heart has less displacement. The interference with heart tracking from non-heart structures may be mitigated by the administration of contrast and use of an IR pulse which both serve to increase the relative signal intensity of the heart (Figure 2).

Our Heart-NAV has several advantages over other “self-NAV” techniques developed to compensate for respiratory motion. Rather than utilizing off-line, retrospective reconstruction algorithms (14,15) or only detecting the respiratory motion (16,17), Heart-NAV tracks heart position and adjusts the imaging volume in real-time using the standard NAV processing pathway. This allows for a relatively straightforward implementation in the clinical environment as no additional hardware or software is needed, and images are immediately reconstructed. Other self-NAV techniques rely on 3D radial or spiral-like k-space trajectories (18–21) which preclude the use of parallel imaging acceleration on clinical scanners. Heart-NAV, however, is compatible with any k-space trajectory, including Cartesian, adding further to its ease of implementation and utility. Lastly, some self-NAVs are based on tracking the central point of k-space from the free induction decay of the net magnetization vector by prolonging the repetition time (22–28). However, with this approach it is not possible to compute the absolute motion, and therefore prospective tracking cannot be performed.

There have been other efforts to reduce the inflow artifact caused by NAV-restore pulse in contrast-enhanced IR whole-heart MRA. Oakes et al. moved the diaphragm-NAV to after the data acquisition (i.e., a trailing NAV), thereby allowing the liver signal sufficient time to recover and obviating the need for a NAV-restore pulse (29). This approach, however, precludes real-time adjustment of the imaging volume position as well as prospective phase reordering and prospective weighted k-space acquisitions. Keegan et al. implemented a delay between the nonselective IR pulse and the NAV-restore pulse so that the inflow artifact shifted away from the pulmonary and systemic veins (30); nevertheless, the artifact can still be present in other regions of the heart. Peters et al. used bellows rather than a diaphragm-NAV to compensate for respiratory motion thereby eliminating the inflow artifact (31); however, the accuracy of bellows in tracking respiratory motion is known to be inferior to that of the diaphragm-NAV (32).

Though our initial results with Heart-NAV are promising, there are several ways in which this strategy may be further developed. Heart-NAV efficacy should be evaluated using higher spatial resolution (1 mm) whole-heart MRA acquisitions suitable for the detection of coronary artery stenosis. In the current study, a 1.5 mm resolution was used because the clinical goal was to assess intracardiac and vascular anatomy in patients with congenital heart disease. The fidelity of Heart-NAV tracking could be improved by using a combination of phased-array surface coil signals to minimize the superimposed signal from static regions surrounding the heart (15,20). Heart-NAV employs end-expiration as a reference position to calculate the respiratory induced-heart motion; however, the optimum respiratory reference may not be end-expiration, and a retrospective iterative algorithm may be required to find the optimal reference position (33,34). Heart-NAV should also be studied in a larger number

of patients to better assess its clinical utility for angiography and 3D late gadolinium enhancement. Lastly, because Heart-NAV excites the same imaging volume as the MRA data acquisition, the steady-state condition of the net magnetization vector is not broken. Therefore, it may be a useful respiratory motion compensation technique when acquiring multiple whole-heart MRA datasets across the cardiac cycle (i.e., 4-dimension cine acquisitions) (35–37).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Schematic diagrams for the non-contrast whole-heart MRA sequence with the conventional diaphragm-NAV (A) and with Heart-NAV (B), and the contrast-enhanced IR whole-heart MRA sequence with the conventional diaphragm-NAV (C) and with Heart-NAV (D). Diaph, diaphragm; Fat sup, fat suppression pulse; FOS, fold-over suppression pulse; NAV, navigator pulse; SP, startup pulses; SSFP, steady-state free precession pulse; T2-prep, T2-preparation pulse; TR, repetition time; IR pulse, inversion recovery pulse; NAV res, navigator restore pulse.

Figure 2.

NAV trace during a Heart-NAV acquisition for non-contrast whole-heart MRA (A) and contrast-enhanced IR whole-heart MRA (B). Solid blue lines: acceptance window (5 mm); horizontal red lines: estimated heart location, lower green lines: accepted whole-heart MRA data; vertical red line: transition from Heart-NAV training phase to the acquisition phase.

Figure 3. Comparison of the diaphragm-NAV and Heart-NAV non-contrast whole-heart 3D MRA sequences in 2 healthy volunteers. Each sequence was acquired using a 5 mm and 10 mm NAV acceptance window. Oblique-plane reformatted images depicting the right coronary arteries (RCA) are shown. Ao, Aorta.

Figure 4. Comparison of the diaphragm-NAV and Heart-NAV contrast-enhanced IR whole-heart 3D MRA sequences in 2 patients. Inflow artifact from the NAV restore pulse (arrow) is seen in the diaphragm-NAV images but not in Heart-NAV images.

Table 1

Image Visual Score and Vessel Sharpness for Whole-heart MRA (n=10).

NAV window	Diaphragm-NAV		Heart-NAV		<i>p</i> -value (Diaphragm-NAV vs. Heart-NAV)	
	5 mm	10 mm	5 mm	10 mm	5 mm	10 mm
RCA visual score	3.67 ± 0.49	3.16 ± 0.52	3.77 ± 0.37	3.15 ± 0.69	0.42	1.00
RCA sharpness	0.64 ± 0.04	0.61 ± 0.06	0.67 ± 0.04	0.61 ± 0.06	0.18	0.86
LAD visual score	3.55 ± 0.51	3.16 ± 0.50	3.53 ± 0.46	3.01 ± 0.67	0.91	0.33
LAD sharpness	0.61 ± 0.07	0.57 ± 0.05	0.60 ± 0.07	0.56 ± 0.06	0.62	0.64
LCX visual score	3.47 ± 0.55	3.05 ± 0.60	3.43 ± 0.53	2.90 ± 0.68	0.83	0.18
LCX sharpness	0.56 ± 0.07	0.52 ± 0.08	0.56 ± 0.09	0.53 ± 0.10	0.85	0.42
Scan time (min)	8.4 ± 2.2	5.7 ± 2.0	7.5 ± 1.7	5.1 ± 1.4	0.041	0.047

Values are mean ± standard deviation. Visual score: 1-poor to 4-excellent. Sharpness measure: 0-blurred to 1-sharp. LAD, left anterior descending coronary artery; LCX, left circumflex coronary artery; RCA, right coronary artery.