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Free-breathing 3D steady-state free precession coronary magnetic resonance angiography: Comparison of four navigator gating techniques

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Abstract

This work compares the performance of four navigator gating algorithms (accept/reject (A/R), diminishing variance algorithm (DVA), phase ordering with automatic window selection (PAWS), and retrospective gating (RETRO)) in suppressing respiratory motion artifacts in free-breathing 3D balanced steady-state free precession coronary MRA. In ten volunteers, the right coronary artery (RCA) or the left anterior descending artery (LAD) was imaged (both if time permitted) at 1.5 T with the four gating techniques in random order. Vessel signal, vessel contrast and motion suppression was scored by the consensus of two blinded readers. In 15 imaged vessels (9 RCA and 6 LAD), PAWS provided significantly better image quality than A/R ($P < 0.05$), DVA ($P = 0.02$) and RETRO ($P = 0.002$). While the quality difference between A/R and DVA was not statistically significant, both algorithms yielded significantly better image quality than RETRO. PAWS and DVA were the most efficient algorithms, providing an approximately 20% and 40% relative increase in average navigator efficiency compared to A/R and RETRO, respectively.

INTRODUCTION

Navigator technology can effectively overcome respiratory motion in free-breathing high-resolution 3D coronary MRA (CMRA) (1–5). In this approach, the respiratory navigator signal is typically acquired from a cranial-caudal cylindrical volume positioned through the right hemi-diaphragm using a 2D selective excitation pulse (6,7). The diaphragmatic motion information is used to select a k-space data set with minimal motion for image reconstruction, which can be done either immediately before data acquisition (prospective gating) or after (retrospective gating). Compared to the retrospective gating algorithm (RETRO) (2), prospective or real-time gating algorithms, including accept/reject (A/R) (8), diminishing variance algorithm (DVA) (9), and phase ordering with automatic window selection (PAWS) (10,11), can provide improved motion suppression, but require rapid real-time navigator processing capability from the scanner hardware. For high-resolution CMRA, the delay between the navigator and the imaging has to be short (e.g., preferably less than 20 ms for

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submillimeter resolution) such that the respiratory motion occurring during image data acquisition is accurately predicted by the preceding navigator echo (12).

Table 1 lists the hardware requirements of the four navigator gating techniques in the order of increased complexity. In the RETRO algorithm, image data is oversampled by a large factor (typically 5) and the decision to retain or discard the acquired data for image reconstruction based on the navigator information is made after the scan. Accordingly, RETRO does not require real-time navigator processing, but is inefficient and may not completely eliminate motion in the k-space data. The A/R algorithm, typically available on commercial scanners with cardiac imaging capabilities, discards image data if the navigator position falls outside a fixed gating window and limits the motion in the acquired data, but a steady diaphragmatic drift from this window can lead to a low navigator acceptance rate and a longer imaging time (13,14). The more sophisticated DVA algorithm overcomes this problem by first acquiring a full data set and then using the remaining scan time to reacquire data associated with the largest displacements from favorable diaphragmatic positions. The most sophisticated algorithm, PAWS, acquires data at all motion levels, which are sorted and grouped into bins. For each bin, k-space is filled according to the bin index and the employed view order, and data acquisition is finished when data from contiguous bins form a complete set of k-space. PAWS provides the combined benefits of both automatic gating window selection and reduced residual motion artifacts within the gating window through view ordering, leading to effective motion suppression in the shortest time. While the performance of these gating techniques had been investigated separately using 3D spoiled gradient echo (SPGR) imaging (10,15,16), a comprehensive pairwise comparison of all four algorithms in a single study would help establish their relative utility. Furthermore, balanced steady-state free precession (SSFP) imaging has replaced SPGR imaging as the state-of-the-art sequence for 3D CMRA due to its superior blood signal-to-noise ratio (SNR) and blood-to-myocardium contrast-to-noise ratio (CNR) (17). The purpose of this study was to compare the performance of RETRO, A/R, DVA and PAWS gating algorithms for free-breathing SSFP 3D CMRA and to determine the statistical significance of the differences in image quality and navigator efficiency.

METHODS

Ten volunteers (8 men and 2 women, mean age of 35 years $\pm$ 14 standard deviation [SD], age range of 23–65 years, no known cardiac diseases) were imaged using a 1.5T clinical scanner (maximum gradient amplitude 33.0 mT/m, slew-rate 120 T/m/s, Excite 14M4 software version; GE Healthcare Technologies, Waukesha, WI, USA). The study protocol was approved by the Institutional Review Board and written informed consent was obtained from all subjects prior to imaging. Subjects were imaged supine with standard eight-channel cardiac phased-array for signal reception and vector ECG gating for cardiac synchronization.

The four gating algorithms were incorporated into an ECG-triggered segmented k-space navigator-gated SSFP 3D CMRA sequence (Fig.1). Prior to CMRA, a breath-hold 2D SSFP cine scout scan was used to determine the optimal trigger delay between the cardiac trigger and diastasis, the period of minimal cardiac motion. The typical imaging parameters were as follows: TR = 4.0 ms, TE = 1.5 ms (partial echo), flip angle = 60°, readout bandwidth = $\pm$ 62.5 kHz, slice thickness = 3 mm, 16 slices, in-plane resolution = 1.0 $\times$ 1.0 mm², 32 echoes per k-space segment, k_z-centric view order. For SSFP magnetization preparation, a 6 Kaiser ramp-up scheme was used to provide a balance between minimizing off-resonance oscillations and providing accurate motion information for navigator gating (18). The time between the navigator and the acquisition of k-space center was approximately 44 ms. A cylindrical diaphragmatic navigator with a 3 cm diameter was positioned through the dome of the right hemi-diaphragm to monitor the cranial-caudal motion of the lung-diaphragm interface. A custom program was developed to collect navigator data and extract motion information using

an image-space least-squares matching algorithm (19). For prospective gating, this program controlled data acquisition in real time (without the need for extra hardware). The response time between the gating program and the pulse sequence was less than 5 ms. For retrospective gating, the same program was used to sort the acquired k-space data at the end of data acquisition and then to write the sorted data into the scanner's memory. All image reconstructions were performed online by the scanner hardware. The RETRO, DVA and PAWS algorithms were fully automated. For the A/R algorithm, the scanner's operator first identified the most superior end-expiratory diaphragmatic position after 15 preparatory cardiac cycles (image data acquisition turned off) and then manually shifted the center of the gating window from this position toward end-inspiration by 1 mm in anticipation of a respiratory up-drift during imaging (14,20). This window was kept fixed throughout the scan regardless of respiratory drift. A gating window of 5 mm was used for A/R, DVA and PAWS gating. A data overscanning factor of 3 (corresponding to a 33% navigator efficiency) was used for DVA and RETRO gating to keep the total study time reasonable. Prospective motion correction (slice tracking) (21) was not used to allow a fair comparison of the original algorithms. All subjects were imaged during free breathing without coaching. The right coronary artery (RCA) and the left anterior descending artery (LAD) were randomly selected for imaging (both vessels were imaged if time permitted). The four gating techniques were performed in randomized order with an inter-sequence delay of less than 30 sec to minimize changes in breathing pattern. Vessel signal, vessel contrast and motion suppression were scored visually by the consensus of two experienced observers blinded to the gating algorithms using a five-point scale (0=very poor, 1=poor, 2=fair, 3=good, 4=very good). These three consensus scores were then averaged to obtain an overall image quality score.

For each CMRA scan, navigator efficiency was calculated as the number of heartbeats in which data were accepted for image reconstruction (128 in the case of 32 echoes per heartbeat) divided by the total number of heartbeats of the scan. The average navigator efficiency for each gating technique was then calculated as the mean of the individual navigator efficiencies over all scanned vessels. Given two gating techniques with respective average navigator efficiencies $eff1$ and $eff2$ ($eff2 < eff1$) and let $\alpha = (eff1 - eff2)/eff2$ be the relative increase in navigator efficiency, the corresponding relative reduction in average scan time can be calculated as: $\beta = (T/eff2 - T/eff1)/(T/eff2) = 1 - eff2/eff1 = 1 - 1/(1+\alpha) = \alpha/(1+\alpha)$, where T is the scan time in the case of 100% navigator efficiency. Note that the relative decrease in scan time is directly related to the relative (and not the absolute) increase in navigator efficiency.

The Kruskal-Wallis one-way analysis of variance (ANOVA) by ranks was used to test the null hypothesis that there was no significant difference in image quality score between the four gating techniques. If such difference was detected, two-tailed Wilcoxon paired-sample signed rank test was performed to determine the statistical significance of the difference between each pair of techniques. One-way ANOVA and two-tailed paired-sample t-tests were used to assess the difference in navigator efficiency. P values of less than 0.05 were considered statistically significant.

RESULTS

CMRA was obtained successfully in all 10 subjects and a total of 15 vessels were imaged (9 RCA and 6 LAD). Figure 2–Figure 4 show reformatted CMRA images obtained from three different subjects. Figure 2 shows an example where all four gating algorithms provided excellent image quality with negligible motion artifacts. Note that the RETRO algorithm limited motion within most k-space data to 5 mm. When RETRO gating failed to restrict motion in k-space data, the resulting images suffered from motion artifacts, leading to image quality inferior to that of prospective gating (Fig.3). Figure 4 shows PAWS more effectively

suppressing ghosting and blurring motion artifacts than the other three algorithms, leading to the best depiction of the LAD and the best overall image quality.

Table 2 summarizes the performance of the four gating algorithms averaged over all imaged vessels ($N = 15$). PAWS gating was found to provide significantly better image quality than A/R ($0.02 < P < 0.05$), DVA ($P = 0.02$) and RETRO ($P = 0.002$) gating. While the quality difference between A/R and DVA was not statistically significant, both algorithms yielded significantly better image quality than RETRO ($P = 0.02$ for A/R vs. RETRO and $P = 0.03$ for DVA vs. RETRO). PAWS and DVA were the most efficient algorithms ($46 \pm 10\%$ for PAWS vs. $47 \pm 11\%$ for DVA, $P = 0.6$), providing significantly higher average navigator efficiency than A/R and RETRO. The relative increase in average navigator efficiency (α) was 18% for PAWS vs. A/R ($P = 0.01$), 39% for PAWS vs. RETRO ($P = 0.0001$), 21% for DVA vs. A/R ($P = 0.02$), and 42% for DVA vs. RETRO ($P = 0.0002$). Correspondingly, the relative reduction in average scan time (β) can be expected to be 15% for PAWS vs. AR, 28% for PAWS vs. RETRO, 17% for DVA vs. AR, and 30% for DVA vs. RETRO. The actual reductions in average scan time were found to match well with these expected reductions: 16% for PAWS vs. AR, 24% for PAWS vs. RETRO, 18% for DVA vs. AR, and 26% for DVA vs. RETRO.

DISCUSSION

Navigator technology has revolutionized CMRA by making it possible to acquire high-resolution scans without breath-holding. These data from ten volunteers show that prospective gating provided better image quality than retrospective gating for navigator-gated 3D SSFP CMRA. RETRO gating cannot guarantee that motion in the k-space data is limited to a small range (typically 3–5 mm for diaphragmatic gating), unless a very large overscanning factor is used at the cost of reduced navigator efficiency and longer scan time. Among prospective gating algorithms, PAWS provided the best motion suppression and the best image quality, which can be attributed to the small motion range at k-space center (the region that has the greatest effect on overall image quality) and the smooth motion distribution in k-space (Fig.4). PAWS is also one of the most efficient gating algorithms (besides DVA) because of its ability to adaptively select a gating window around the most likely diaphragmatic position even in the case of respiratory drift (13).

Several other investigators have performed similar but less comprehensive comparison studies that corroborate these results. A preliminary study by Jhooti et al demonstrated that PAWS gating provided significantly improved image quality compared to DVA gating (10). Du et al scanned 8 healthy subjects and found that A/R gating with a 4 mm window provided significantly better and 16% shorter 3D SPGR CMRA than RETRO gating with an overscanning factor of 5 (15). Note that an overscanning factor of 5 results in very long scan time (more than 10 min per imaging plane for a heart rate of 60), which is often unacceptable for clinical applications. Here, an overscanning factor of 3 was chosen to keep the total scan time reasonable and correspondingly A/R gating with a larger 5 mm window was found to provide significantly better and 9% shorter 3D SSFP CMRA than RETRO gating, indicating similar results. In another study, Langreck et al compared the motion adapted gating (3D-MAG) algorithm with conventional A/R gating for 3D SPGR CMRA in 21 cardiac patients and found that both techniques provided similar image quality but A/R gating failed in 2 patients due to low navigator efficiency (16). Similar to PAWS, 3D-MAG is a multi-level algorithm where data are acquired at multiple motion levels to overcome respiratory drift, but unlike PAWS, 3D-MAG does not guarantee smooth motion distribution within the gating window. This discrepancy may explain the observed significant image quality improvement of PAWS gating compared to A/R gating in our study, as opposed to no improvement of 3D-MAG gating compared to A/R gating in (16). While A/R gating did not fail in our study (the lowest navigator efficiency was 20%), patients with cardiopulmonary diseases are known to

often have erratic breathing patterns (e.g., irregular cycle, strong drift) compared to disease-free volunteers such as the ones studied here.

This study has several limitations. Patients with clinically suspected coronary artery disease were not included. It is worth noting that such patients can exhibit complex breathing patterns and variable heart rates, particularly over a long period of scan time (about 25–30 min per coronary territory) as required in this study. This variability in patient condition may lead to unwanted bias in observed image quality and navigator efficiency that cannot be attributed to the gating algorithm. Another limitation is the number of imaged subjects and coronary vessels. While relatively small, it was sufficient to derive statistically significant differences between the gating techniques. The left circumflex artery (LCx) was not imaged, and the RCA and the LAD were both imaged only in six out of ten subjects. Furthermore, the data acquisition window during each heartbeat employed in this study (approximately 130 ms) was longer than the typical 60–100 ms window reported in the literature. Since each coronary artery had to be imaged four times with different gating algorithms, these were done to keep the study time tolerable for study subjects. Despite the increased window, the average image quality for prospective gating techniques was rated as good or better, indicating robustness against cardiac motion. Prospective motion correction (slice tracking (21)), while capable of improving image quality, was not implemented here to facilitate a fair comparison of prospective gating with retrospective gating and to better highlight the difference in performance between the original gating techniques.

In conclusion, prospective gating provided better image quality in less scan time than retrospective gating and the PAWS gating algorithm was found to be the most efficient and effective for free-breathing 3D SSFP CMRA.

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Figure 1.

Schematics of the navigator-gated 3D SSFP CMRA sequence. After an ECG trigger delay (TD), a diaphragmatic navigator echo (NAV) was acquired, followed immediately by a fat saturation pulse (FATSAT) to suppress epicardial fat. A magnetization preparation (6KR) consisting of 6 Kaiser ramp-up dummy repetitions (data acquisition turned off) was then used to drive spins into steady state for subsequent SSFP data acquisition during the diastasis. The described sequence is repeated for every cardiac cycle until the image data is fully acquired.

Figure 2. Reformatted CMRA images obtained with a) RETRO, b) A/R, c) DVA, and d) PAWS gating algorithms demonstrating similarly excellent image quality of the RCA with negligible motion artifacts. Corresponding motion distributions of k-space segments used in the final image reconstruction are shown on the right. Note that RETRO gating limited motion within most k-space data to 5 mm, which was the same as the gating window employed by prospective gating algorithms. Here k-space segments are numbered according to their positions along k_y , going from one edge of k_y -space (segment 0) through the center (segment 63) to the other edge (segment 127).

Figure 3. Reformatted CMRA images obtained with a) RETRO, b) A/R, c) DVA, and d) PAWS gating algorithms. Corresponding motion distributions of k-space segments used in the final image reconstruction are shown on the right. While prospective gating (A/R, DVA and PAWS) provided superior image quality with negligible motion artifacts and excellent depiction of the RCA, RETRO gating suffered from blurring artifacts due to substantial motion (larger than 5 mm) in k-space data.

Figure 4. Reformatted CMRA images obtained with a) RETRO, b) A/R, c) DVA, and d) PAWS gating algorithms. Corresponding motion distributions of k-space segments used in the final image reconstruction are shown on the right. In this example, PAWS gating provided the smoothest motion distribution in k-space and the best depiction of the LAD and surrounding structures.

Table 1

Hardware requirements of the four navigator gating techniques listed in the order of increased complexity.

	Real-time navigator processing	Real-time image data storage
RETRO	No	No
A/R	Yes	No
DVA	Yes	No
PAWS	Yes	Yes

Table 2

Comparison of image quality, navigator efficiency, and scan time of free-breathing 3D SSFP CMRA acquired with four navigator gating techniques (N = 15).

	Image quality score	Navigator efficiency (%)	Scan time (sec)
RETRO	2.5 ± 1.0	33 ± 0	320 ± 61
A/R	3.0 ± 0.7	39 ± 10	290 ± 106
DVA	2.9 ± 0.8	47 ± 11	238 ± 74
PAWS	3.3 ± 0.7	46 ± 10	243 ± 73