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Self-gated MRI of multiple beat morphologies in the presence of arrhythmias

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Abstract

Purpose—Develop self-gated MRI for distinct heartbeat morphologies in subjects with arrhythmias.

Methods—Golden angle radial data was obtained in 7 sinus and 8 arrhythmias subjects. An image-based cardiac navigator was derived from single-shot images, distinct beat types were identified and images were reconstructed for repeated morphologies. Image sharpness, contrast and volume variation were quantified and compared to self-gated MRI. Images were scored for image quality and artifacts. Hemodynamic parameters were computed for each distinct beat morphology in bigeminy and trigeminy subjects and for sinus beats in patients with infrequent premature ventricular contractions.

Results—Images of distinct beat types were reconstructed except for two patients with infrequent premature ventricular contractions. Image contrast and sharpness were similar to sinus self-gated images (Contrast = 0.45 ± 0.13 and 0.43 ± 0.15 ; Sharpness = 0.21 ± 0.11 and 0.20 ± 0.05). Visual scoring was highest in self-gated images (4.1 ± 0.3) compared to real-time (3.9 ± 0.4) and ECG-gated cine (3.4 ± 1.5). ECG-gated cine had less artifacts than self-gating (2.3 ± 0.7 and 2.1 ± 0.2), but was affected by misgating in two subjects. Among arrhythmia subjects, post-extrasystole/sinus (58.1 ± 8.6 mL) and interrupted sinus (61.4 ± 5.9 mL) stroke volume was higher than extrasystole (32.0 ± 16.5 mL; $p < 0.02$).

Conclusion—Self-gated imaging can reconstruct images during ectopy and allowed for quantification of hemodynamic function of different beat morphologies.

Keywords

arrhythmias; non-periodic motion; cardiovascular magnetic resonance; retrospective cine; navigators; real time; golden angle; radial; non-Cartesian; sensitivity encoding

Introduction

Non-invasive imaging of left ventricular (LV) systolic function is the foundation for clinical management of cardiac patients (1). Cine magnetic resonance imaging (MRI) provides highly accurate and reproducible assessment of ventricular structure and function in sinus rhythm patients (2), but significant cardiac motion inconsistency during arrhythmias can lead to image artifacts and incorrect assessment of cardiac function, repeat imaging, increased patient discomfort, and additional healthcare costs. Furthermore, the hemodynamic performance of those ventricular ectopic beats is largely ignored.

Multi-shot cine MRI acquires data across multiple cardiac cycles, requiring periodic motion. However, this may not be the situation in arrhythmia patients. The R-wave of an ectopic contraction may not be detected because of an irregular or distorted QRS complex or the rhythm may change, resulting in incorrect assignment of cardiac phase data. While prospective cine is commonly used for arrhythmia patients, it does not capture end-diastolic cardiac phases and may underestimate ventricular diastolic volume (3,4). Despite these well-known limitations, the use of different gating approaches for arrhythmia patients has not been previously reported nor have society guidelines discussed their use (4).

Arrhythmia rejection (AR) is often used to improve image quality in patients with arrhythmias, but there are several limitations. AR typically compares the duration of each RR-interval to a predefined reference. If the interval exceeds a certain tolerance, then data acquired during extrasystolic and postextrasystolic beats are rejected and reacquired (5). However, if the R-wave is irregular, delayed, or widened, it may not be detected and the measured RR can fall within the tolerance, leading to incorrect acceptance of ectopic beat data. The limitations of arrhythmia rejection effects are illustrated in Figure 1.

Recent single-shot (real-time) imaging techniques have utilized a combination of non-Cartesian k-space sampling, parallel imaging, and iterative reconstructions with novel regularization metrics to image the heart with sufficient spatial and temporal resolution to observe ectopic contractions (6–9). Nevertheless, the spatiotemporal resolution and signal-to-noise ratio of single-shot techniques could be further improved if additional data from similar heartbeats were correctly synthesized (10).

The aim of this study was to develop a self-gated approach to image and quantify the hemodynamic parameters of distinct beat morphologies in arrhythmia patients. To assess self-gated reconstruction of ectopic motion, LV slice volume variation, image edge sharpness and contrast in arrhythmia subjects were compared to images reconstructed from sinus rhythm subjects who underwent breath-held and free-breathing scans. Interrupted, extra- and postextrasystolic beat hemodynamic parameters, derived from self-gated MRI, were compared to ECG-gated cine MRI in patients with bigeminy, trigeminy and infrequent premature ventricular contractions.

Methods

Human Subjects

This study was approved by the University of Pennsylvania Institutional Review Board and all subjects gave written, informed consent to participate.

Seven patients in sinus rhythm (1 male, 48.3 ± 14.0 years old) being evaluated with MRI for hypertrophic cardiomyopathy (n=3), pulmonary arterial hypertension (n=2), or other non-ischemic cardiomyopathy (n=2) were enrolled.

The arrhythmia group consisted of eight adult patients (2 males, 52.6 ± 25.5 years old) undergoing diagnostic cardiovascular MRI and had an ongoing arrhythmia during MRI: 2 had ventricular bigeminy, 4 had trigeminy, and 2 had sporadic premature ventricular contractions.

Image Acquisition

Cardiac MRI was performed on a 1.5 T clinical imaging system (Avanto, Siemens Healthcare, Erlangen, Germany) equipped with 40 mT/m magnetic field gradients, body RF transmit and a 32-channel, anterior and posterior RF receiver array and wireless electrocardiogram (ECG) gating.

2D golden angle radial balanced steady-state free-precession (bSSFP) was acquired with the following parameters: TE = 1.4 ms, repetition time (echo spacing) = 2.8 ms, number of radial k-space points per radial projection = 128, field of view = $220\text{--}300 \times 220\text{--}300$ mm², bandwidth = 1000 Hz/pixel, flip angle = 70 degrees, slice thickness = 8 mm, golden angle = 111.25 degrees. Waveform delay correction was applied to each gradient axis to reduce eddy currents (11). The golden angle trajectory permitted retrospective reconstruction at multiple spatiotemporal resolutions while preserving uniform azimuthal sampling density (12). 12,000 radial projections per slice were acquired and a subset of these projections were used for breath-held, free-breathing, and respiratory self-gated reconstructions. Each 2D scan was repeated for each short axis slice with full LV coverage. In sinus rhythm volunteers, a 15–20 sec instructed breath-hold was performed within each 33 sec slice scan. A second acquisition with full LV coverage was performed during free-breathing. In arrhythmia patients, only free-breathing data was collected. An overview of the scans and reconstructions performed for the different patient groups is shown in Figure 2A.

Breath-held ECG-gated, multi-shot, cine MRI was performed with 2D Cartesian bSSFP and the following imaging parameters: TE = 1.07 – 1.31 ms, repetition time = 2.14 – 2.62 ms, matrix = $156 - 256 \times 192 - 256$, field-of-view = $227.5\text{--}350 \times 280\text{--}420$ mm², BW = 930 Hz/pixel, slice thickness = 8 mm, gap = 2 mm and temporal resolution = 24.7 – 36.5 ms. Short axis slices were matched to radial bSSFP. In two arrhythmia subjects (subjects 1 and 2), prospectively ECG-gated, multi-shot, cine MRI was performed with TE = 1.19 ms, repetition time = 2.38 ms, matrix = 156×192 , field-of-view = 227.5×280 mm², BW = 930 Hz/pixel, slice thickness = 8 mm, gap = 2 mm and temporal resolution = 33.5 – 36.5 ms.

Image Reconstruction

An overview of the reconstruction approach is shown in Figure 2B. First, single-shot (real-time) images were produced using a Tikhonov-regularized, non-Cartesian SENSE algorithm (13) with radial projections $N_\theta=34$, TR = repetition time $\times N_\theta = 95.2$ ms, frame rate FR = TR (sliding window factor = 1) (Gadgetron, National Institutes of Health, Bethesda, MD) (14). These parameters were previously shown to be sufficient to estimate continuous LV slice volume up to a heart rate = 120 beats-per-minute (bpm) (15,16). RF detector sensitivity profiles were estimated from all acquired radial views using a non-uniform fast Fourier transform and Kaiser-Bessel gridding kernel (17,18).

LV slice volume (V) was estimated using level set segmentation and provided an image-based self-gating signal (16,19,20). Images were arranged in a 3D stack of size $N_X \times N_Y \times N_T$, where $N_{X,Y}$ was the image dimensions and N_T was the total number of image frames; the typical size was $128 \times 128 \times 12,000$. Papillary muscles were excluded from the segmented volume. Segmentation of all slices and phases in a single patient required approximately 30 minutes post-processing.

Slice volume served as the navigator signal for self-gating. The slice volume signal was segmented into individual beats v_i where $i \in [1, \dots, N]$ and N is the total number of observed beats. Beat segmentation was performed using local volume maxima/minima identification as previously described (16,21,22).

Repeatedly observed beat morphologies were determined by calculating 4 parameters for each beat v_i : beat duration RR_i , initial slice volume $V_{BEG,i}$, minimum slice volume $V_{MIN,i}$, and final slice volume $V_{END,i}$. These parameters were used to detect the occurrence of ectopic contractions, preload changes, and respiratory motion (Figure 2C). When an ectopic contraction disrupted diastolic filling of a cardiac cycle, the systolic duration of the normal contraction was estimated as the time between $V_{BEG,i}$ and $V_{MIN,i}$. This was used to estimate heart rate duration and reassign cardiac phase information to projections acquired prior to the ectopic contraction. Beat annotation required approximately 5 minutes of post-processing per patient for all slices.

For each beat, radial projections were assigned to a normalized cardiac phase after nonlinear temporal scaling (23). A breath-held cardiac self-gating signal from one volunteer in sinus rhythm is shown in Figure 3A. The small volume variation confirms a single beat morphology. The overlapping volume curves are shown in Figure 3B and 3C.

Respiratory self-gating was performed by monitoring respiratory-induced variation of the navigator signal. After selection of the beat type of interest with an initial set of parameters (RR_i , $V_{BEG,i}$, $V_{MIN,i}$, and $V_{END,i}$), respiratory self-gating was performed by accepting only beats when $V_{BEG,i}$ was within range during end-expiration. The acceptable end-expiratory range of $V_{BEG,i}$ was determined separately for each slice.

Self-gated reconstruction was performed by sorting each projection into $N_p=30$ cardiac phases for sinus rhythm and 35–40 ms bins for arrhythmia patients and performing iterative Tikhonov-regularized, non-Cartesian SENSE reconstruction implemented on Matlab (The

MathWorks, Natick, MA). Three reconstructions were performed in sinus rhythm subjects to investigate image quality and sinus volume variation: breath-held, free-breathing, and respiratory self-gated (see Figure 2A). Respiratory and arrhythmia self-gated reconstruction was performed in all arrhythmia subjects.

Premature Ventricular Contraction Prevalence and Scan Efficiency

The mean number (N) of radial projections used to reconstruct each frame and temporal resolution ($TR=RR/Np$) were reported for all subjects. Beat prevalence was computed using the Pan-Tompkins algorithm on synchronized ECG data (24). The scan efficiency was the number of beats of a particular morphology used for reconstruction (beat %) divided by the total number of observed beats (total %).

Volume Variation

For each self-gated reconstruction, volume variation was

$$\delta_V = \frac{1}{N_p} \sum_{i=1}^{N_p} \sigma_i,$$

where σ_i is the standard deviation of slice volume observed at cardiac phase i . The volume variation of repeated heartbeats was measured to determine motional consistency of similar beats.

Image Quality

Image quality was quantified with image contrast and edge sharpness (25). Image contrast C at end-diastole in a mid-ventricular slice was

$$C = |I_B - I_M| / (I_B + I_M),$$

where I_B was the mean intensity of a circular region-of-interest (ROI) in the LV blood pool and I_M was the mean intensity of a similarly sized ROI in the LV septum.

Edge sharpness S was

$$S = \sqrt{(x_{0.8} - x_{0.2})^2},$$

where $x_{0.8}$ ($x_{0.2}$) was the position along a radial projection intersecting the mid-septal myocardial border where the intensity was 80% (20%) of maximum. The mean sharpness across the cardiac cycle was reported for all slices and reconstructions.

Hemodynamics

Cine and self-gated LV images were semi-automatically segmented with active contours (ITK-SNAP, Philadelphia, PA) to estimate slice volumes and EDV, ESV, SV, and EF. Mean bias between cine and self-gated images was

$$\Delta EDV = |EDV_{CINE} - EDV_{SG}|.$$

ESV, SV, EF were similarly calculated.

Statistical Analysis

Significant differences in the number of projections, temporal resolution, image contrast, sharpness, volume variation, and hemodynamic measurements between cine and self-gated images were estimated using a one-way Kruskal-Wallis test at a $p < 0.05$ level of significance (Matlab, The MathWorks, Natick, MA). All statistical tests were two-tailed.

Results

Scan Efficiency

Beat prevalence and scan efficiency determined the number of projections available for reconstruction (N). Among all arrhythmia beat morphologies observed, interrupted sinus beats tended to be the least frequently available at end-expiration ($N = 61.7 \pm 28.6$) and post-extrasystolic or sinus beats the most ($N = 87.8 \pm 51.9$; Table 1 and Figure 4A). Arrhythmia-related beats were available less often than breath-held cardiac self-gated sinus beats ($N = 65.7 \pm 23.4$ and 150.8 ± 43.3). Individual results for sinus patients appear in Supporting Table S1 and for arrhythmia subjects in Supporting Table S2.

Volume Variation

Cardiac and respiratory self-gated images of arrhythmia-related beats had comparable volume variation to breath-held cardiac self-gated scans ($\delta = 4.8 \pm 2.2$ and $\delta = 4.6 \pm 1.7$) and lower variation than free-breathing cardiac self-gating exams (no respiratory self-gating, $\delta = 7.3 \pm 4.3$) (Table 1 and Figure 4B). Among arrhythmia-related beats, extrasystole had the highest volume variation ($\delta = 6.0 \pm 2.5$).

Image Quality

In sinus patients, image contrast in ECG-gated cine images was comparable to breath-held cardiac self-gated images ($C = 0.57 \pm 0.03$ and 0.56 ± 0.10) and was higher than free-breathing or respiratory cardiac self-gated images (0.39 ± 0.15 and 0.43 ± 0.15 , $p < 0.05$; Figure 4C). Image sharpness was higher in breath-held cardiac self-gating than in free-breathing and comparable to respiratory self-gating ($p < 0.05$, Figure 4D). Arrhythmia self-gated image contrast and sharpness was similar to respiratory self-gated images in sinus subjects.

Visual scoring was performed to quantify image quality and artifact level in mid-ventricular slices in arrhythmia patients by two physicians with CMR expertise using the criteria listed in Supporting Table S3. Image quality was highest in self-gated images (4.1 ± 0.3) in comparison to real-time (3.9 ± 0.4) and ECG-gated cine (3.4 ± 1.5) (Supporting Table S4). Although cine had two 5.0 scores, two other scores were < 2.0 due to mis-gating artifact in the arrhythmia subjects. ECG-gated cine resulted in the best artifact level score (2.3 ± 0.7) relative to real-time (1.9 ± 0.4) and self-gating (2.1 ± 0.2).

Hemodynamics

In sinus rhythm subjects, there were no significant differences in EDV, ESV, SV, or EF between cine and self-gated reconstructions (Table 2). In arrhythmia subjects, there were no significant differences between beat types in EDV, ESV, or EF. There were significant differences between interrupted sinus and extrasystolic stroke volume ($p < 0.01$, Figure 4E). Images from three arrhythmia subjects are shown in Figure 5 (subjects 1, 2, and 6 in Supporting Table S2). Videos illustrating the variable loss of image quality in ECG-gated cine acquisitions and improvement with self-gating are available (Supporting Video S1 – S6).

1. Bigeminy Hemodynamics—Arrhythmia self-gating imaged all cardiac phases of beats in patients with bigeminy (Figure 5A–B; subjects 1 and 2 in Supporting Table S2). In subject 1, each beat had distinct hemodynamic properties (interrupted sinus beat EF=51.9% and extrasystole EF=62.9%). Extrasystole had higher ESV and lower SV and EF compared to the interrupted sinus beat. In subject 2, a complex pattern of bigeminy was observed. The premature ventricular contraction occurred at different times from the onset of the interrupted sinus R-wave, leading to couplets of different durations (short couplet RR = 1091.5 ms and long couplet RR = 1404.6 ms). Prospective cine captured only a brief portion of the long couplet and neither end-diastolic nor end-systolic phases were captured and EDV was lower than in self-gated images.

2. Trigeminy Hemodynamics—In trigeminy patients, three beat morphologies were observed: interrupted sinus, extrasystole, and post-extrasystole. Retrospective cine with arrhythmia rejection only reconstructed images of the post-extrasystolic morphology, since data acquired from interrupted sinus and extrasystolic beats were rejected. There were no significant differences in hemodynamics measured with cine and self-gating of post-extrasystolic/sinus beats (Table 2). The differences in beat morphology in subject 6 can be seen on both temporal projections and associated slice volume curves (Figure 5C).

3. Infrequent Premature Ventricular Contraction Hemodynamics—In two patients, premature ventricular contractions were not frequent enough to produce self-gated images of ectopic beats at all slice positions for assessment of global hemodynamic function. However, self-gated images of sinus beats uncorrupted by arrhythmias were produced. In subjects 7 and 8, hemodynamic function was compared to function obtained cine MRI with arrhythmia rejection. In subjects 7 and 8, differences in SV and EF were due to lower ESV measured via the self-gating.

Discussion

We assessed the feasibility of self-gating to reconstruct images of distinct heartbeat morphologies in subjects with arrhythmias. Self-gating is commonly used to reduce respiratory motion artifacts in free-breathing exams (26–28) and the potential to reduce cardiac motion artifacts in arrhythmia patients has been recognized (29–31), however this is the first time cardiac self-gating was used to reconstruct common types of arrhythmia for quantification of hemodynamic function. Image quality was comparable to cardiac and

respiratory self-gating in sinus rhythm subjects, suggesting that the repeated ectopic beats were consistent. Self-gating did not require patient-specific adjustment of prospective or retrospective scan parameters and captured the hemodynamics of all contractions, including interrupted sinus and extrasystolic heartbeats without the need for instructed breath-holding or repeat scans.

Image Quality

In sinus rhythm patients, breath-held cardiac self-gated ventricular volumes were consistent because of good patient compliance and absence of rhythm disturbances. Image contrast and edge sharpness were comparable to cine MRI and thus cardiac self-gating did not introduce additional blurring or artifacts that would limit quantification of hemodynamic function. In comparison, free-breathing self-gating had reduced image consistency, trended toward hemodynamic bias and decreased image quality, largely attributed to respiratory motion. Respiratory self-gating significantly improved motion consistency and image quality with low hemodynamic bias, despite lower scan efficiency.

Among patients with rhythm disturbances, volume variation of ectopic and post-ectopic beats was comparable to respiratory self-gated beats in sinus patients. This suggested that these beats had consistent motion and that, for patients with moderate arrhythmia prevalence, there were sufficient occurrences of a distinct beat type to allow for self-gating at every slice position.

In two subjects with bigeminy, it was possible to obtain high quality prospective cine scans. As expected from previous studies of prospective MRI (3,4), we observed that EDV and EF were lower than arrhythmia self-gated scans. While it was possible to obtain images of interrupted sinus and extrasystolic beats in subject 1 with prospective gating, the breath-hold duration was prolonged compared to sinus subjects and might not be manageable for other subjects. Even though the spatial or temporal resolution may be decreased to maintain a similar breath-hold duration, this necessitates a repeat scan with consideration of new parameters. Self-gating successfully imaged all beats in the complex rhythm of subject 2 which was not possible with prospective gating.

Significance of Ectopy

Ventricular arrhythmia in the form of premature ventricular contractions is common, and most often benign in patients with underlying normal hearts (32). However, in some patients, they can induce or worsen the underlying cardiomyopathy (33,34). Comprehensive evaluation of a patient's ectopic function may be important for understanding the contribution of different premature ventricular contractions to the cause of cardiomyopathy. In patients with structural heart disease and arrhythmias, it can be unclear whether an echocardiographic or MRI-derived EF is less than 35% (eligible for ICD) or 40–45% due to actual significantly decreased cardiac function or corrupted imaging in the setting of mildly decreased function. Using self-gating, an EF can be estimated for each distinct beat or the multiple EFs measured can be combined with beat prevalence to provide time-average cardiac performance. Prospective studies must be designed to prove the potential of these techniques for improving risk assessment in patients. Future studies using this approach are

planned to measure regional differences in wall thickening in different beat types and, combined with LGE imaging, begin to quantify regional impairments that likely precede global hemodynamic impairment.

Alternatives and limitations

An alternative approach to self-gating is single-shot (real-time) MRI, which may provide high spatiotemporal resolution scenes of every heartbeat with much less data than would be required by the Nyquist sampling criteria (35–42). Based on the low variation of ventricular volume in the image-based navigator in this work and in other reports (18), it is apparent that single-shot MRI has sufficient spatiotemporal resolution to characterize beat-to-beat ventricular volumes with low bias compared to cine MRI (43). In addition, a compressed sensing reconstruction which incorporates a spatio-temporal total variation (TV) constraint can further improve image quality and is demonstrated in Supporting Videos S7–S9 (44).

One limitation of this cardiac self-gating technique is the perturbation of k-space sampling uniformity that occurs with multi-shot golden angle radial trajectories (25). Although consecutive, single-shot golden angle radial projections provide near-uniform sampling, retrospective sorting of non-consecutive beats results in sampling patterns that have reduced uniformity. However, the increased number of projections associated with multi-shot imaging decreases undersampling and generally improves image quality.

A second limitation of the technique is the need for an accurate volume navigator signal in the short axis. Although we obtained slice volume curves in both sinus and arrhythmia subjects at positions throughout the LV, other applications such as long-axis imaging or atrial CMR may require modification of the technique.

Third, cardiac self-gating requires that ectopic beats be observed multiple times at the same respiratory phase. Therefore, infrequent ectopic contractions, varying ectopic patterns, and heavy respiratory motion will decrease the likelihood of imaging a particular beat morphology. Prolonged scans or instructed breath-holding would increase the likelihood of observing and quantifying additional beat morphologies. In patients with infrequent ectopic events, the arrhythmia may fall below the level of clinical significance. In these situations, arrhythmia self-gating can quantify sinus beat hemodynamics similar to cine MRI with arrhythmia rejection.

Finally, very high heart rates or short ectopic RR durations may limit the accuracy of the navigator signal derived from real-time MRI data. The shortest RR interval was approximately 400 msec (interrupted sinus beat) and at such short intervals the temporal footprint will limit the timing accuracy of the gating signal. In a previous study animal study, ventricular end-diastolic and end-systolic volumes were accurately quantified at heart rates up to 140 beats-per-minute ($RR = 430$ msec), however timing accuracy will be reduced for heart rates above this threshold or very short interrupted sinus beats(15).

Conclusions

We developed a reconstruction method for self-gated MRI that permitted high spatiotemporal resolution imaging of distinct beat morphologies. The feasibility of this approach was determined in normal subjects and was further demonstrated in eight subjects with varying patterns of arrhythmia. This approach may reduce the number of non-diagnostic cine MRI exams due to frequent ectopic contractions and permit quantification of ectopic beat function to better understand cardiac function in arrhythmia.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Potential mechanisms for retrospective cine image corruption in the presence of arrhythmias.

A) Normal LV volume in sinus rhythm (end-diastole = red points and end-systole = black).

During sinus rhythm, consecutive k-space shots are acquired, with one shot acquired per heartbeat. K-space is colored according to the heartbeat in which it was sampled. In this example, k-space was fully sampled after 4 shots.

B) Potential image corruption due to missed R-wave detections. Two ectopic contractions occurred (green and yellow boxes), but were not detected by the physiologic monitor. The corrupted portions of k-space acquired during these beats are shown with a hashed pattern in the k-space diagram below.

C) Image corruption could also occur due to decreased scan efficiency when ectopic beats are correctly identified and rejected (red boxes). The decreased scan efficiency may result in an unachievable breath-hold duration and respiratory motion artifacts.

Figure 2.

Study design of arrhythmia self-gated MRI. **A)** Overview of the acquisitions, image reconstructions, and analysis performed. Self-gating specific analysis are denoted by asterisks **B)** A single-shot (real-time), sliding window, SENSE-based reconstruction allowed for LV slice volume quantification via segmentation of the endocardial blood volume. Volumetric-based arrhythmia detection and beat morphology categorization was performed and the final self-gated, multi-shot reconstruction combined projections acquired during similar beats using the assigned cardiac phase. **C)** Annotation of the image-based navigator. Local maximum (red points) were detected and utilized to identify individual beats. For each beat, the beat duration RR, initial slice volume V_{Beg} , minimum slice volume V_{Min} , and final slice volume V_{End} were quantified. The slice volume V corresponds to a subject in trigeminy from which three distinct beat morphologies were observed (post-extrasystole, interrupted sinus beat, and extrasystole). Post-extrasystole was characterized by a long RR, high V_{BEG} .

low V_{MIN} , and high V_{END} while interrupted sinus had a short RR, high V_{BEG} , low V_{END} and low V_{MIN} and extrasystole had a short RR, low V_{BEG} , high V_{MIN} , and high V_{END} . Variation of V_{BEG} within a beat morphology was attributed to respiratory motion and limits for V_{BEG} were manually assigned for each slice to capture beats within the same respiratory state.

Figure 3.

Comparison of cine and breath-held self-gating in a sinus rhythm subject. **A)** A mid-ventricular volume curve (blue) was derived from real-time data. Scanning started while the patient was free-breathing, then the patient was instructed to hold their breath (green), the patient began breathing again and then the scan was stopped. Prior to and after the breath-hold (projection number 0 – 2000 and 7000–8000), the effects of respiration caused detectable variations in slice volume. **B)** Comparison of individual beat curves illustrate the close agreement of the navigator signal and confirm a single beat morphology. **C)** The

variation within the beat morphology is small throughout the cardiac cycle (solid line represents the mean of the accepted beats and the shaded areas represent the range). **D)** End-diastole and **E)** End-systole from cine MRI. **F)** Projection through the LV demonstrates cardiac motion. **G)** Comparable self-gated images at end-diastole, **H)** end-systole, and **I)** temporal motion.

Figure 4.

Reconstruction parameters (A), image quality (B–D), and stroke volume (E) and ejection fraction (F) obtained using the self-gating approach from sinus patients during breath-held (BH), respiratory gated (RG), and free-breathing acquisitions (FB) and in patients with rhythm disturbances (AR). Hemodynamic measurements in patients with rhythm disturbances illustrate variation among beat types, in comparison to cine (PES: post-extrasystolic beat, IS: interrupted sinus beat, ES: extrasystolic beat).

Figure 5. Reconstruction of different beat morphologies in three subjects with rhythm disturbances. For each subject, a short axis image at end-diastole is shown with a red line indicating the orientation of projection images (space-time) **A)** Subject 1 had bigeminy and prospective cine was performed across interrupted sinus and extrasystolic beats, but extrasystolic end-diastolic frames were not scanned. Self-gated MRI fully reconstructed both beat morphologies. **B)** Subject 2 experienced two alternating patterns of bigeminy during imaging. Self-gating fully reconstructed both patterns, while prospective gating captured

only one couplet and excluded end-diastolic frames from the extrasystolic beat. **C)** Subject 6 had trigeminy and all three beat morphologies were observed, but cine reconstructed only the post-extrasystolic beat.

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Table 1

Reconstruction parameters and image quality in sinus and arrhythmia subjects

	Reconstruction Parameters				Image Quality	
	RR (ms)	TR (ms)	N	contrast	sharpness	variation (%)
<i>Sinus</i>						
CINE	975.0 ± 126.6	34.5 ± 1.3		0.57 ± 0.03	0.31 ± 0.06	
SG _{BH}	1009.1 ± 130.7	33.7 ± 4.5	150.8 ± 43.3	0.56 ± 0.10	0.25 ± 0.09	4.6 ± 1.7
SG _{RG}	998.5 ± 123.6	33.2 ± 4.0	89.1 ± 25.5	0.43 ± 0.15	0.20 ± 0.05	4.7 ± 1.7
SG _{FB}	986.0 ± 111.8	32.7 ± 4.1	184.7 ± 32.2	0.39 ± 0.15	0.20 ± 0.05	7.3 ± 4.3
<i>Arrhythmia</i>						
CINE	1107.4 ± 402.8	38.6 ± 9.9		0.50 ± 0.14	0.16 ± 0.06	
SG _{AR} [†]	1046.9 ± 355.5	37.5 ± 0.6	65.7 ± 23.4	0.45 ± 0.13	0.21 ± 0.11	4.8 ± 2.2
<i>post-ES or sinus</i>	1053.3 ± 263.5	37.5 ± 0.4	87.8 ± 51.9	0.44 ± 0.12	0.24 ± 0.13	4.8 ± 1.5
<i>IS</i>	948.6 ± 466.8	37.3 ± 0.6	61.7 ± 28.6	0.46 ± 0.12	0.21 ± 0.08	4.4 ± 1.7
<i>ES</i>	1193.2 ± 366.3	37.4 ± 0.4	66.7 ± 28.4	0.44 ± 0.15	0.19 ± 0.09	6.0 ± 2.5
p-value *	0.92	<0.001	<0.001	<0.001	0.06	<0.01

* Kruskal-Wallis test between SG_{BH}, SG_{RG}, SG_{FB}, SG_{AR}[†] SG_{AR} reported for all beat types and individual (post-ES, IS and ES)

Patient specific results are included in Supporting Table 1 and Table 2

Abbreviations:

ES: extra-systole

IS: interrupted sinus

SG_{BH}: Cardiac self-gating during breath-holdSG_{RG}: Cardiac and respiratory self-gating (end-expiration; sinus subjects)SG_{FB}: Cardiac self-gating without respiratory gating (free-breathing)SG_{AR}: Cardiac and respiratory self-gating (end-expiration; arrhythmia subjects)

TR: Temporal resolution (RR duration/30 cardiac phases)

N: Number of radial projections used for image reconstruction

Table 2

Hemodynamic parameters in sinus and arrhythmia subjects

	Volumetric Measurements			
	EDV (mL)	ESV (mL)	SV (mL)	EF (%)
<i>Sinus</i>				
CINE	104.9 ± 9.7	28.1 ± 9.8	76.8 ± 8.7	73.4 ± 7.9
SG _{BH}	101.3 ± 7.4 (3.4)	25.9 ± 9.6 (7.8)	75.4 ± 10.2 (1.8)	74.5 ± 8.9 (1.5)
SG _{RG}	103.0 ± 16.9 (1.8)	28.0 ± 10.8 (0.3)	75.0 ± 13.4 (2.3)	73.0 ± 7.7 (0.5)
SG _{FB}	95.4 ± 13.4 (9.0)	24.9 ± 4.7 (11.4)	70.5 ± 13.8 (8.2)	73.5 ± 5.6 (0.0)
<i>Arrhythmia</i>				
CINE	94.7 ± 22.9	52.8 ± 39.7	51.9 ± 12.2	54.1 ± 19.2
post-ES or sinus	85.2 ± 16.4 (10.0)	37.5 ± 24.0 (29.0)	60.0 ± 3.8 (15.6)	62.8 ± 13.7 (16.1)
IS	96.6 ± 12.0 (2.0)	39.6 ± 2.0 (25.0)	61.9 ± 5.4 (19.3)	60.8 ± 3.5 (12.4)
ES	68.0 ± 27.1 (28.2)	36.0 ± 15.9 (31.8)	32.0 ± 16.5 (38.3) [‡]	54.2 ± 7.6 (0.2)
p-value [*]	0.18	0.86	0.02	0.41

Value in parentheses indicates percent bias from CINE.

^{*} Kruskal-Wallis test between CINE, post-ES or sinus, IS and ES[‡] p<0.05 between SV of ES and IS morphologies.

Patient specific results appear in Supporting Table 1 and Table 2

Abbreviations:

ES: extra-systole

IS: interrupted sinus

SG_{BH}: Cardiac self-gating during breath-holdSG_{RG}: Cardiac and respiratory self-gating (end-expiration; sinus subjects)SG_{FB}: Cardiac self-gating without respiratory gating (free-breathing)

TR: Temporal resolution (RR duration/30 cardiac phases)