Respiratory-Resolved Fat-Suppressed Cardiac Cine MRI

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Target Audience MR physicists and clinicians interested in pulse sequence design, image reconstruction, cardiac imaging, and ventricular function.

Purpose In most cardiac MR functional imaging applications, breath holding, navigator gating, or retrospective motion correction is typically used to "freeze" respiration at a single phase to minimize motion artifacts. However, in certain disease states, such as a pericardial constriction and diastolic dysfunction, changes in cardiac function throughout the respiratory cycle are of interest[1-3]. In this work, we present a free-breathing 2D cine technique that simultaneously resolves multiple cardiac and respiratory phases. Our technique achieves fat-suppressed steady-state contrast and concurrently tracks respiratory motion of the heart using a self-navigated alternating repetition time (ATR) balanced steady-state free precession (bSSFP) sequence.

Methods By bridging the slice-select rephasing gradients of an ATR sequence, we enabled acquisition of a 36-point 1D navigator along k_z (Fig. 1). Because this navigator readout is acquired during the unused short TR (TR_2) of an ATR sequence[4], it requires no additional scan time and exploits the high-SNR steady-state signal during TR_2 to track respiratory motion throughout the scan. Our approach was inspired by a wideband-SSFP technique developed by Lee, *et al.*, for respiratory-gated cardiac imaging at 3 T[5]. In our work, imaging was performed at 1.5 T and utilized the steady-state ATR contrast for fat suppression.

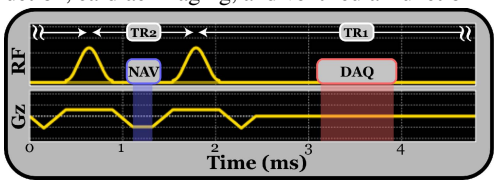

Figure 1. Navigated ATR SSFP pulse sequence. Bridging slice-select rephasing lobes during TR_2 enables acquisition of 1D navigators along k_z.

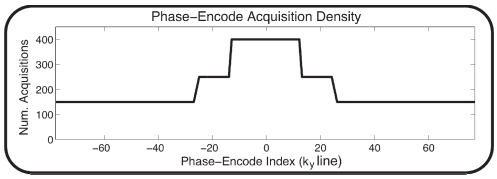

Figure 2. Phase-encode acquisition density, with higher density near the center of *k*-space.

Healthy volunteers were scanned on a GE 1.5 T scanner using the RTHawk real-time environment[6] (HeartVista, Inc., CA) and an 8-channel cardiac receive array. A 2DFT readout was used with a distributed phase-encode segmentation scheme. All 156 phase encodes were divided into 13 segments containing 7 paired[7] phase encodes (14 views per segment, 67-ms temporal resolution). Six pairs were spaced uniformly across *k*-space, and the seventh was used to reacquire the center of *k*-space for temporal redundancy. To sample the entire RR interval, each *k*-space segment was repeated for a duration spanning 1.15 times the expected RR interval. After acquiring all segments, the central third of *k*-space was further oversampled using a 2.4-second linear acquisition. This acquisition scheme was repeated sequentially 10 times during free breathing while simultaneously recording ECG and self-navigation data for retrospective determination of cardiac and respiratory phase. Figure 2 shows the acquisition density achieved by this segmentation scheme for a 2.5-minute scan. The central *k*-space lines were acquired a total of 400 times to sample all cardiac and respiratory phases with high probability.

Self-navigator magnitude data were processed using principal component analysis[8] followed by bandpass filtering (passband = 0.07 – 0.5 Hz) to extract a respiratory waveform. Peak detection was used to separate the respiratory waveform into periods of expiration and inspiration, and a respiratory phase was assigned to each acquired readout based on the amplitude of the navigator signal. Similarly, a cardiac phase was assigned to each acquired readout using the elapsed time from the previous ECG R-wave trigger. Each phase encode was non-uniformly sampled at many different cardiac and respiratory phases, and linear interpolation was used to resample the acquired phase encodes onto a uniform 9x15 grid of respiratory and cardiac phases. The following acquisition parameters were used: FOV = 30x30 cm^2, res. = 1.5x1.9 mm^2, flip angle = 50°, slice thickness = 6 mm, TR_1/TR_2 = 3.65/1.15 ms, 510 dummy views to reach steady state.

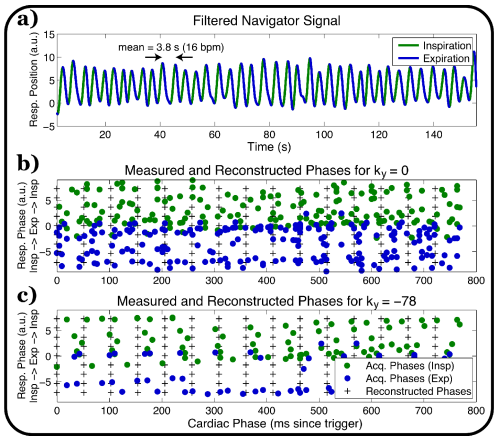

Figure 3. Navigator waveform and acquired phases from a free-breathing scan. **(a)** Filtered navigator signal is divided into inspiration (green) and expiration (blue) to track respiratory phase. **(b-c)** Each phase encode is acquired at a nonuniform set of cardiac and respiratory phases, with more dense sampling of central phase encodes **(b)** than outer phase encodes **(c)**. Acquired data are interpolated linearly onto a grid of cardiac and respiratory phases.

Results The filtered navigator signal from a 2.5-minute free-breathing scan (Fig. 3a), shows a 16-bpm respiratory waveform, which agrees closely with the rate measured by respiratory bellows. The cardiac and respiratory phase locations of all 400 acquisitions of k_y index 0 (Fig. 3b) and all 150 acquisitions of k_y index -78 (Fig. 3c) are dispersed among the uniform grid of reconstructed phases. Reconstructed end-systolic and end-diastolic images from 5 of 9 respiratory phases show respiratory motion of the heart and diaphragm (Fig. 4).

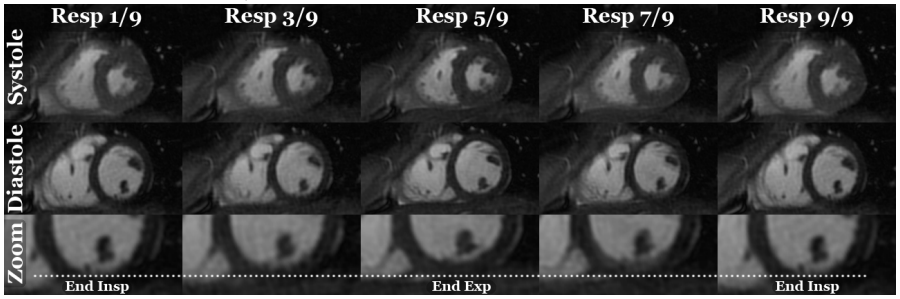

Figure 4. Five respiratory phases from a free-breathing short-axis scan are shown at systole and diastole. 15 cardiac phases and 9 respiratory phases were reconstructed, enabling both "cardiac-cine" display at a fixed respiratory phase and "respiratory-cine" display at a fixed cardiac phase.

Discussion & Conclusion The proposed technique enables data from a single free-breathing scan to be displayed in a standard "cardiac-cine" format for a fixed respiratory phase, or in a "respiratory-cine" format for a fixed cardiac phase. In this preliminary work, no attempt was made to minimize scan duration. The high degree of temporal redundancy could permit substantial acceleration using compressed sensing or parallel imaging techniques. Future work includes extension of this technique to a 3D acquisition, which will require acceleration to maintain reasonable scan duration. In conclusion, we have demonstrated a technique for respiratory-resolved fat-suppressed 2D cardiac cine imaging with self-navigated respiratory motion tracking during the unused TR_2 of an ATR sequence.

References [1] Wu, *et al.*, Proc 19th ISMRM, p. 4359. [2] Wu, *et al.*, Proc 20th ISMRM, p. 3848. [3] McConnell, *et al.*, JACC 6:917-19, 2013. [4] Leupold, *et al.*, MRM 55:557-65, 2006. [5] Lee, *et al.*, Proc 17th ISMRM, p. 4643, 2009. [6] Santos, *et al.*, Conf Proc IEEE Eng Med Biol Soc. 2:1048-51, 2004. [7] Bieri, *et al.*, MRM 54:129-37, 2005. [8] Luo, *et al.*, Proc 21st ISMRM, p. 2581, 2013.