Cardiac Cine MRI for Mice with Myocardial Infarction using 3D Self-gated Radial Gradient Echo

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Introduction

Cine magnetic resonance imaging (MRI) is a powerful technique for functional and volumetric evaluation of myocardial infarction (MI) and subsequent left ventricular (LV) remodeling in mice. Conventionally, data acquisition of cine MRI is performed with a multi-slice sequence with electrocardiogram (ECG) triggering. However, post-MI hearts are often quite arrhythmic and with fluctuating heart rate, which can significantly impair the accuracy of ECG gated cine MRI. Another factor compromising the conventional cardiac MRI is the poor quality of ECG often seen at ultra-high field. Moreover, conventional multi-slice cine MRI has poor resolution along slice selective dimension and may induce errors in volumetric analyses, especially for post-MI hearts which have considerable structural variation due to LV remodeling. In this study, we address these issues by introducing a self-gated cine MRI sequence based on 3D radial gradient echo. Self-gating enables retrospective cardiac phase determination regardless of fluctuating heart rate in MI mice. 3D radial acquisition provides isotropic spatial resolution of 133 µm. In addition, use of a radial MRI sequence in cardiac cine imaging has advantages such as inherent tolerance to motion [1] and undersampling artifacts [2]. Although tolerance to undersampling in radial acquisition allows higher scan acceleration, 3D k-space acquisition is generally time-consuming especially for high resolution imaging. Therefore, compressed sensing (CS) reconstruction is employed for further acceleration, which results in acceptable scan time (~14 min) even for mice with severe MI.

Method

The proposed sequence was composed of fixed slab selective excitation and subsequent radial asymmetric echo acquisition (Fig.1a). Self-gating signal acquisition was inserted between slab refocus and readout dephasing gradients. Slab selective excitation covering only the heart region (~1.5 cm thickness) enabled accurate detection of respiratory and cardiac motion in the self-gating signals (Fig.1b); respiratory and cardiac motion were extracted as different frequency components (60-90 and 400-600 min^{-1}, respectively). In order to test the accuracy of the self-gating, heart rate of a normal mouse was changed by controlling depth of anesthesia during a ~11 min scan; isoflurane concentration increased to 3.0% (from 1.5%) at ~100 sec after starting the scan and changed back to 1.5% around 360 sec (Fig.2). For comparison, ECG signals were recorded during the scan. In the test of the self-gate accuracy, gradient amplitude was reduced to 10% of that in cine MRI acquisition (i.e. x10 larger FOV) so as to avoid interference from gradients to ECG signals.

All MR scans were performed in a 9.4T 31 cm bore scanner (Agilent Technologies, Inc.). MI was introduced by ligating the left coronary artery of seven NOD/SCID Gamma mice (Jackson Lab, ~30g). At one month post-surgery, 3D cine MR scans were performed. During MR scans, mice were anesthetized with inhaled 1.5% isoflurane mixed with room air. The mice were positioned prone and a single loop surface coil (~1.5 cm diameter) was placed under the left side of the chest. The mice were free-breathing. Temperature was maintained at 37±1 °C with a custom built water heated holder. For comparison, cine MR imaging was performed on age-matched mice without the left coronary artery ligation. Sequence parameters for cine MRI were TR=4.5 ms, TE=0.7 ms and # of views=184320, nominal FA=15°, FOV=28x28x28 mm^3, and scan time=14 min.

In image reconstruction, acquired data were sorted according to their cardiac phase extracted from the self-gating signals. The sorted radial k-space data were split into 16 time frames (~11520 views/frame) and then each of them was gridded onto a Cartesian k-space [3]. Matrix size of the reconstructed image was 210x210x210 (133 µm isotropic nominal resolution); thereby undersampling factor was ~12 compared to the Nyquist criterion. In order to reduce streaking and noise-like (incoherent aliasing) artifacts due to undersampling, CS reconstruction was applied with sparsity constraints (l1-regularization) of 4D wavelet and total variation (three spatial and one temporal dimensions) [4].

Results

Results from the MR self-gating test are shown in Fig.2. Heart rate drop and recovery were detected in ECG signals as the isoflurane concentration was changed from 1.5 to 3.0% and back to 1.5%. Consistent heart rate changes were found in MR self-gating signals, demonstrating the MR self-gating captured cardiac motion accurately.

Reconstructed cardiac cine images at end-diastole and end-systole for a normal mouse and mice with small and large infarct are shown in Fig.3. The inherent denoising property in CS reconstruction removed not only undersampling artifacts but noise in the images (images without CS reconstruction are not shown here). For a normal heart, uniform LV wall thickness and contractile function were seen (Fig.3a). In contrast, MI mice showed thin scar in the infarcted LV anterior wall (yellow lines in Fig.3b,c) and contractile dysfunction for those lesions were conspicuous (almost no contraction between end-diastole and end-systole). For mice with large MI (Fig.3c), a significant increase of the volume of the left ventricle was seen, indicating adverse LV remodeling.

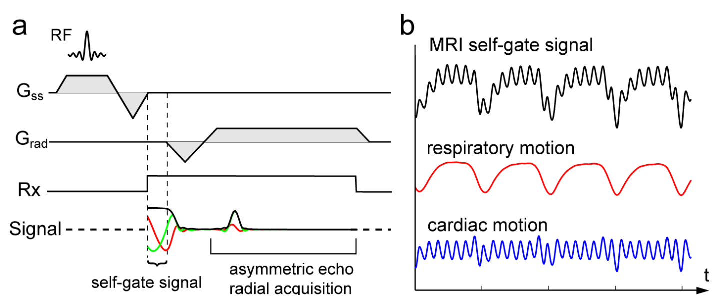

Figure 1. Sequence diagram of 3D radial gradient echo with self-gating (a) and cardiac motion detection from the self-gating signals (b)

Conclusions

A radial gradient echo sequence with cardiac self-gating has been introduced for 3D cine imaging of MI mice. Accuracy of the MR self-gating was validated by comparing with ECG signals. Compressed sensing reconstruction predominantly removed undersampling artifacts and noise, resulting in reasonable scan time in animal experiments (14 min). The proposed methods visualized dynamics of cardiac function for MI mice with various infarct sizes; the 3D self-gated cine MRI technique is robust for MI mice with severe arrhythmia associated with significantly adverse LV remodeling.

Acknowledgements

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References

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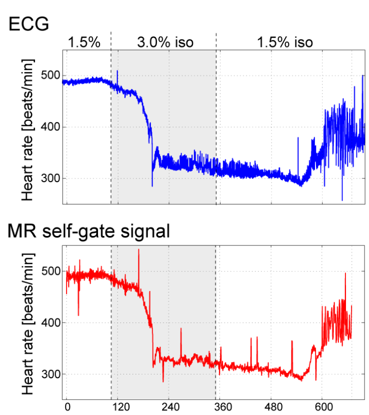

Figure 2. Validation of MRI self-gating.

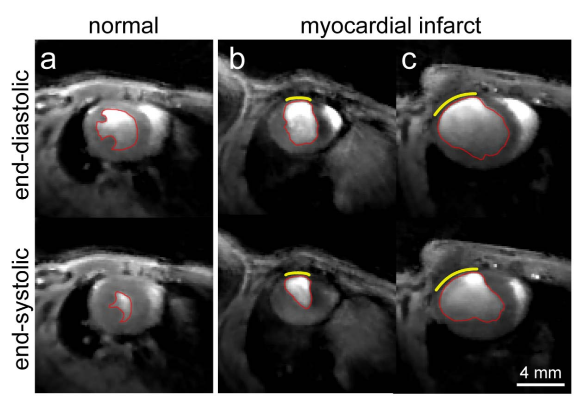

Figure 3. Short-axis MR images of a normal mouse (a) and myocardial infarcted mice with small and large infarct sizes (b, c) at end-diastole (top) and end-systole (bottom).