A Robust Method for Auto-Synchronized Cine MRI in the Mouse at 7 T

B Hiba[1,2], N Richard[2], M Janier[1,2], P Croisille[1,2]

[1]Platform ANIMAGE, Rhône-Alpes Genopole, Lyon, France
[2]Creatis, CNRS UMR 5515, Inserm U 630, Lyon, France

Abstract

ECG-gated cardiac MRI in the mouse is hindered by many technical difficulties in ECG signal recording inside static and variable high magnetic scanner fields. The present study proposes an alternative robust method of acquiring auto-gated cine images in mouse heart. In our approach, a motion synchronization signal is extracted from the echo peak MR signal of a non-triggered radial acquisition. This signal is then used for both cardiac and respiratory retrospective gating before cine image reconstruction. Highly asymmetric echoes were acquired to achieve the radial k-space sampling, in order to avoid radial acquisition related artifacts and to increase auto-gating robustness. In vivo experiments demonstrated the feasibility and robustness of self-gated cine-MRI in the mouse heart at 7T.

1. Introduction

Genetically modified mice are widely used as models for human cardiac disease because the genome of mice has been well-characterized and distinct genetic modifications can be achieved. Thanks to hardware adaptation and pulse sequence optimization to meet the imaging requirements of the small and rapidly beating mouse heart, micro-MRI has over the last few years become one of the main non-invasive tools used to characterize the mouse heart [1,2].

Electrocardiograms (ECG) are conventionally used for cardiac gating to synchronize MR data acquisition and cardiac cycle with precision. The rapid switching of magnetic field gradients and radio frequency (RF) magnetic field pulsing, however, induce an electromotive force in the conductive loop formed by the subject's body and the ECG electrodes [3].

The purpose of the present study was to develop a Self-Gated (SG) cine-MRI method for cardiac applications in the mouse. The challenge was to detect the very fast (up to 600 beats per minute (bpm)) movement of the beating mouse heart within non-triggered MRI data and to achieve retrospective cardiac and respiratory gating. Acquisition efficiency has to be conserved, to obtain a microscopic cine-MRI within a reasonable examination time.

2. Methods

The echo peak signal, regularly recorded at k-space center during the non-triggered radial scanning, corresponds to the sum of the transverse magnetization across the entire Field Of View (FOV). In bright blood cardiac cine-MRI techniques, fluctuations in echo peak correspond to changes in blood volume within the excited slice, and to tissue movements into or out of the excited volume due to heart contraction. The largest echo peaks correspond to end-diastolic and the smallest to end-systolic cardiac cycle phases. The echo signal can be so used for retrospective reconstruction [4] to obtain the cardiac cine-images.

Respiratory motion, which induces changes in structures and in steady-state conditions in the image volume because of tissue movements, can also produce supplementary echo peak signal fluctuations. In the mouse, under experimental conditions, significant respiratory motion comes mainly during inspiration, which occurs every 10-15 heart beats and takes about one-and-a-half to two ECG cycle. SG signal perturbation due respiratory motion in mice can be located and the corresponding data eliminated ahead of reconstruction, so as to achieve a retrospective respiratory gating.

The study was carried out on six healthy 129SV male mice of 15 weeks of age, weighing 24 ± 2 g. MR acquisitions were performed under Anesthesia on a 7 T horizontal-bore MR scanner. A birdcage coil with an inner diameter of 72 mm was used for RF excitation and a surface coil of 15 mm for MR signal reception.

After scouting for the long and short-axis orientations in the heart using a non-triggered FLASH sequence. Ten contiguous non-triggered self-gated acquisitions were performed in the short-axis orientation to cover the entire heart from atrium to apex (slice thickness = 1 mm). With a cardiac rate of 396 + 36 bpm, and allowing for a 30% increase in acquisition time due to respiratory gating, the mean acquisition time was 3 min 14 sec per slice. SG cine

images were also acquired in the long-axis orientation of the heart, with a spatial resolution of 117 μm and with a slice thickness of 0.75 mm.

For self-gated acquisitions, a 2D Projection-Reconstruction (PR) sequence was designed to achieve an azimuthal k-space sampling range of 0–360°. To increase the amplitude and readability of the SG signal extracted from the echo peaks, highly asymmetric echoes were acquired with a short echo time. The PR sequence parameters were: echo asymmetry = 5%; TE/TR = 1.3/8 ms; band width = 64 kHz; number of samples per view = 134; number of views = 512 and flip angle of 30°

Self-gated image reconstruction was performed off-line on an external PC using a homebuilt C++ program, as follows:

1) SG trigger detection: the self-gating signal was firstly filtered using a non-parametric zero-order kernel regression [5] with an Epanechnikov kernel. A kernel window half-size of 2-4 samples was found to give the best filtering effect. Each point of the SG signal with an amplitude greater than that of its neighbors in a bilateral local neighborhood equivalent to the filter kernel window half-size was considered a local maximum.

2) Cardiac cycle determination on the SG signal: each interval between two consecutive SG triggers corresponds to a potential cardiac cycle. Only inter-peak intervals having a duration of the order of the cardiac cycle were selected as valid cardiac cycles, thereby eliminating most of the data acquired during respiratory motion. To take account of variations in cardiac cycle duration, the histogram of detected cycle duration was mapped over the whole SG signal, and the most frequently occurring duration was considered as the main cardiac cycle duration. A tolerance interval for cardiac cycle duration around the main value was then chosen by setting lower and upper thresholds in the light of the histogram. Only radial MR data corresponding to the selected interval on the SG signal were used for cine image reconstruction.

3) Retrospective cardiac gating: the selected SG triggering peak series was then used to generate a time stamp for each remaining readout. This time stamp was representative of the time interval between the acquisition of each particular k-space readout and the immediately preceding SG peak. Radial MR data were then regrouped into groups with a temporal thickness of TR per group. These groups corresponded to different cardiac frames of the cine image.

4) Cine image reconstruction: the K-space data of each cardiac phase were resampled onto a Cartesian grid with a Kaiser-Bessel interpolation kernel [6] The Kaiser-Bessel interpolation function used in the gridding step was computed with a window-width of L=3 pixels of the Cartesian grid in both directions, and a half-bandwidth product $\beta=\pi.L$. A 2D back-FFT was finally applied in the k-space domain (k_x,k_y) for each cardiac phase, to obtain the cine image.

3. Results

SG signals obtained with different positions and orientations in the myocardium exhibited modulations due to the cardiac and respiratory motion (Fig. 1). MR data acquired during respiratory motion were eliminated according to SG signal processing algorithm leading to a mean rejection rate of 28.1% of the total acquired data set.

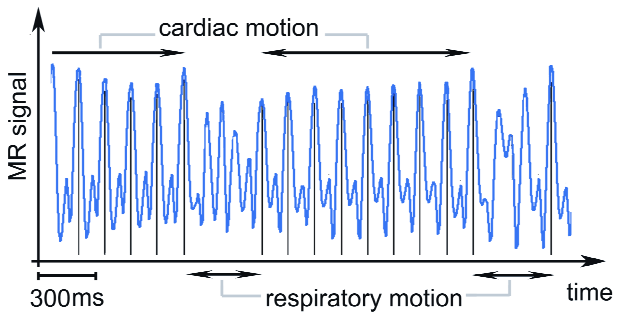

Figure 1. A cardiac self-gating signal obtained in mouse heart. Vertical peaks present triggering peaks detected by the retrospective gating algorithm.

Short and long-axis self-gated cine images were successfully acquired in six mice at different locations covering the whole mouse heart. Figure 2 shows some examples of cardiac images obtained using the self-gating technique.

The obtained cine images show that the self-gating technique gives a very good depiction of the papillary musculature and of the heart valves, and that Self-gated images do not suffer from the flow artifact usually visible in the phase direction of Cartesian images. Additionally, the blood out-slice effect, due to excessive blood circulation velocity in the mouse heart during some phases of the cardiac cycle, was not pronounced in self-gated images obtained with the short-TE PR acquisition, which provides high quality images of all the cine frames.

Finally, the self-gating technique provides a complete covering of cardiac cycle, in contrast to the partial cover provided by the ECG-gated technique. In the chosen example, the number of frames was 18 for the self-gated cine images.

4. Discussion and conclusions

In the present study, the radial SG strategy for cine MRI in humans proposed by Larson et al. [7] was adapted for mouse applications. The major advantage of this strategy is that the SG signal is directly obtained from the

image data with a relatively high temporal resolution equal to the minimum TR provided by the scanner hardware and pulse sequence.

Radial sampling of the k-space may suffer from a specific artifact, described by Peters et al. [8], when the real radial trajectory misses the k-space center because of non-adjusted and/or delayed gradients. This artifact leads to an intra-view variation in the echo peak position depending on the projection angle. If it is not taken into account, this effect could compromise the reproducibility of cardiac retrospective gating over the acquisition.

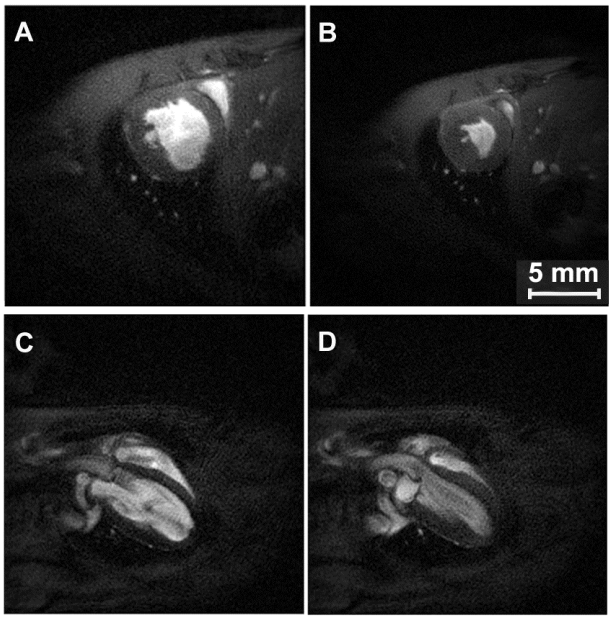

Figure 2. End-diastolic and end-systolic images obtained in the short-axis orientation (A, B respectively) and in the long-axis orientation (C, D respectively) in a mouse heart using the self-gating strategy.

In case of symmetric echo acquisition, the effects of such an off-center radial trajectory on the SG signal could be severe, because of the high-intensity gradients necessary for high spatial and temporal resolution cine-MRI. To decrease gradient intensity, we implemented a radial k-space sampling schema with highly asymmetric echo readouts (5%). This significantly reduced gradient intensity, and hence the off-center radial trajectory artifact. Additionally, the use of a short echo time (1.3 ms), allowed by asymmetric echo acquisition, limits the SG signal decay due to the magnetization transversal relaxation and reduces the phase accumulation due to flow and motion occurring during the readout window.

Large variations in blood volume, occurring in slices crossing myocardium cavities, provide an SG signal that is quite sufficient for robust retrospective cardiac gating without any parameter optimization during the SG signal-processing step. However, for short-axis slices located in the apex, the small variations in in-slice blood volume between systolic and diastolic phases slightly change the SG signal. Therefore, to avoid synchronization errors due to this slight variation, the SG signal was computed by averaging several MR signal values from a limited number of samples (3 points) around the echo peak in each radial readout. In this way, even motion occurring outside blood zones in the myocardium apex can produce a sufficient SG signal for retrospective gating procedure.

In our approach, all SG signals, obtained in various orientations and positions in the mouse heart, exhibited fluctuations due to respiratory motion (Fig. 1). In most cases, these fluctuations allowed automatic detection and elimination of respiratory motion using the retrospective gating algorithm previously described. In some SG cine data sets, depending on the velocity and orientation of the respiratory motion, respiratory fluctuations were not sufficiently pronounced to be automatically separated from those induced by cardiac motion. In the totality of these cases, residual non-detected respiratory fluctuations were successfully tracked on the SG signal and then eliminated using a manual procedure provided by the post-processing program.

The combination of radial k-space scanning and of self gating enabled high-quality images of the cardiac structure and function to be acquired with minimal artifacts. In fact, the SG technique eliminated the variable TR artifact which the Cartesian ECG-gating technique suffers from [9], while the PR technique is less sensitive to inter- and intra-view motion [4], which appears as ghosts in the phase direction of Cartesian images. Additionally, the robustness against motion artifacts provided by the PR technique and by optimal respiratory gating may explain the clear definition of small in-motion cardiac structures, such as papillary muscles and heart valves, obtained using the SG strategy.

In this study, we report a robust self-gating strategy for cardiac and respiratory motion, to achieve high quality cine-MRI in small animal hearts, avoiding the difficulties of ECG signal recording inside the MR scanner high magnetic fields.

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Address for correspondence

Bassem HIBA Ph.D.
Plateforme ANIMAGE
Bât. CERMEP - Hopital Neuro-Cardiologique
59 Boulevard Pinel,
69677 Lyon – France
Bassem.hiba@cermep.fr