Accelerated High Frame Rate Mouse CINE CMR Using Retrospective Triggering and Compressed Sensing Reconstruction

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Background

Cardiovascular Magnetic Resonance (CMR) of heart anatomy and function is an important diagnostic tool to study heart disease. Functional parameters are derived from a dynamic series of images through the cardiac cycle (Cine CMR). Commonly, Cine MR images of the mouse heart are recorded with a relatively low frame rate (typically less than 25 frames per cardiac cycle) because the very high mouse heart rate (400 - 600 bpm), and the speed of acquisition is constrained by hardware limitations (gradient amplitudes and slew rates). However, a significant drawback of low temporal resolution Cine CMR evaluation of heart function is that details of myocardial motion during the phases of systolic contraction and diastolic relaxation go undetected. In this abstract, we introduce a new technique to obtain very high frame rate cine CMR movies of the mouse heart in a total acquisition time considerably shorter than the time needed for a gold standard reconstruction. The technique exploits the retrospective triggering acquisition scheme to produce an undersampled and random k-space filling that allows for a compressed sensing (CS) image reconstruction as shown in Fig 1. As a result, cine CMR is demonstrated with a very high frame rate (93 frames/cycle) within short acquisition time (~ 6-8 min). The technique was validated in mice.

Methods

The scanning was performed with a 9.4 T Bruker animal scanner, where a total of N = 8 mice (29 ± 2 g) were included in the experiment. The 'gold-standard' 93-frames Cine movies were acquired with a retrospectively triggered FLASH sequence (matrix = 192x192, TR/TE = 4.7/2.35 ms, 1.5x undersampling GRAPPA reconstruction). Cardiac and respiratory synchronization was obtained from a navigator echo with homebuilt software in Matlab 8.1 using local maximum detection algorithm to determine the start of the cardiac cycle and omit acquisitions during respiratory motion. As illustrated in Fig. 1, to make a movie, the k-lines are binned in short time frames (γ = duration of 1 time frame). Because k-lines are measured asynchronously with the cardiac cycle, k-space is filled randomly. The full 'gold-standard' acquisition was performed by acquiring 2500 shots of 192 phase encoding k-lines, resulting in a total acquisition time of 24 min. Compressed sensing (CS) reconstruction of high temporal resolution Cine MRI movies of the mouse heart is demonstrated using 3-fold (3-X) and 4-fold (4-X) reduction by taking the first 800 or 600 shots from the 2500 shots of the full acquisition.

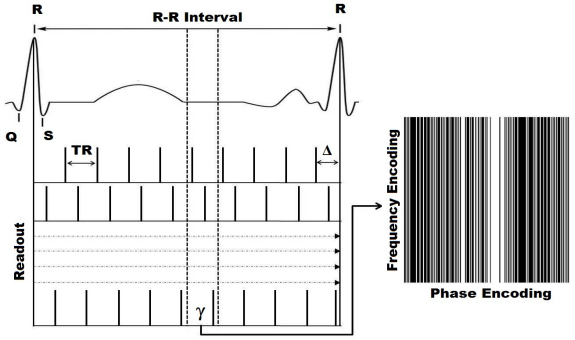

Fig 1. The acquisition scheme and its effect on the k-space trajectory of one of the time frames after some repetitions, resulting in an undersampled and random k-space filling.

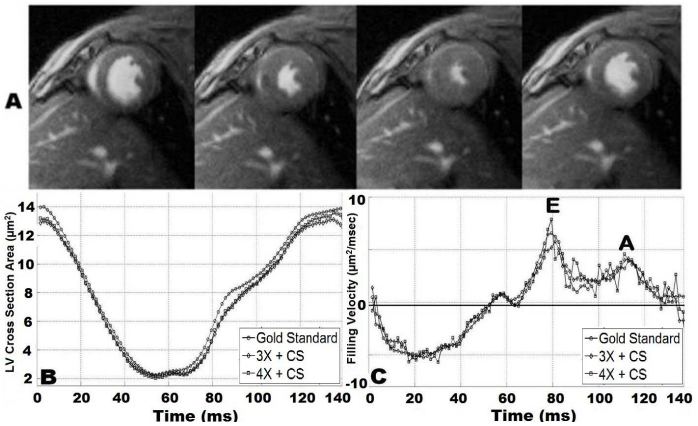

Fig 2. A) 4 out of 93 time frames and the corresponding B) LV section surface area and C) filling velocity vs. time curves, where the early (E) and later (A) filling phases could be identified clearly. Surface areas and filling velocities derived from non-accelerated and accelerated acquisitions are near to identical.

Results

Four still frames from a 93-frames Cine movie of the gold standard reconstruction are shown in Fig 2. Global contractile function was assessed by segmentation of the LV endocardial contours as a function of time through the cardiac cycle, resulting in a LV cavity cross section surface vs. time curve as shown. From the time derivative of the curve, the ejection and filling velocity vs. time curve was determined, which served to assess diastolic function by means of the E/A ratio, where E and A are the early and late filling phases induced by ventricular relaxation and atrial contraction respectively. For each mouse, the full acquisition was used as the gold-standard movie, to which the accelerated movies were subsequently compared. Fig 3 shows two still frames from a gold standard reconstruction compared to 3-X and 4-X accelerated CS reconstructions. The CS reconstructions are visually indistinguishable from the full gold-standard dataset and provide superior image quality in terms of SNR and CNR. As an example, the SNR and CNR at end-diastole for the 3-X and 4-X CS reconstructions (n=8) were, 78±16 and 98±23, and 67±22 and 96±22 respectively. To evaluate the effect of CS reconstruction on derived heart functional parameters, the differences in the E/A between gold standard and 3-X, and 4-X CS reconstructions were statistically compared in a Bland-Altman analysis as shown in Fig 4. For the 3-X CS and 4-X CS accelerated reconstructions, differences were evenly distributed around a bias value of 2.7% and 6%, with 95% limits of agreement [-2.7%, 8%] and [-0.9%, 13%] respectively, which are in very good agreement.

Discussion and Conclusion

Further improvements and higher accelerations might be achieved by undersampling in two dimensions, frequency and phase encoding directions, which can be realized by radial k-space filling trajectories. Additionally, tempo-spatial undersampling could be performed by incorporating the time axis, which also may facilitate higher acceleration factors without significant losses in image quality and derived cardiac functional parameters. Finally, each k-space line has an equal acquisition chance, which is good for the gold standard acquisition, because it results in homogeneous k-space filling and averaging. However, for the CS reconstruction a variable-density distributed filling scheme, which could be achieved by adapting the k-space acquisition trajectory, would be more favorable. Currently, for a single slice with FOV = 3 X 3 cm^2 and in-plane resolution = 156 μm, reconstructing 93 frames/cardiac cycle in ~6-8 minutes becomes possible. Thus multi-slice imaging becomes more feasible. In conclusion, we have achieved very high frame rate mouse heart Cine MRI by exploiting a retrospective triggering acquisition scheme in combination with compressed sensing reconstruction. 3- and 4-X accelerated movies were of similar quality as non-accelerated movies and resulted in similar cardiac functional parameters.

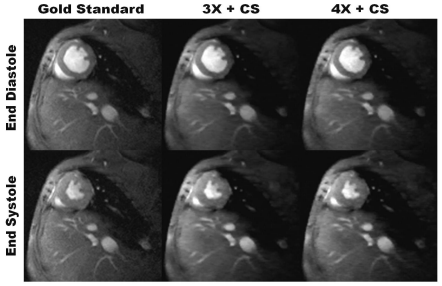

Fig 3. Comparison of full acquisition, 3-X CS and 4-X CS reconstructions.

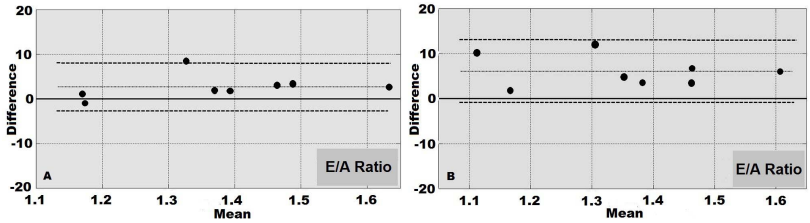

Fig 4. The Bland Altman plot for the E/A ratio with 95% limits of agreement between gold standard and the A) 3-X CS and B) 4-X CS reconstructions.

Acknowledgement

This work is supported and funded by Imaging Science and Technology/Eindhoven (IST/e).

References

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