Development of Real-time Magnetic Resonance Imaging of Mouse Hearts at 9.4 Tesla – Simulations and First Applications

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Target audience: Scientists and clinicians interested in fast cardiac MRI in rodents.

Purpose: The determination of ventricular volumes in mice using MRI is a well-established but time-consuming procedure. Furthermore, the duration of the anesthesia can have an influence on the determined parameters, especially in animals with severe heart disease. Finally, the segmented acquisition in cine MRI requires pro- or retrospective cardiac triggering and respiratory gating, which makes the investigation of arrhythmic animals difficult. The aim of this study was to evaluate the feasibility of real-time imaging to assess left-ventricular function in mice, i.e. to perform the data acquisition without cardiac and/or respiratory gating. A highly accelerated radial imaging technique using both parallel imaging and compressed sensing was developed for this purpose.

Theory: Using ultra-fast radial gradient echo sequences with a TR of < 2 ms allows for acquiring approximately 50-80 read-outs in a cardiac cycle of a mouse. In order to divide one cycle into at least ten heart-phases, a maximum of eight read-outs per timeframe can be used. The reconstruction technique, which was developed to reconstruct highly undersampled datasets can be separated into two parts: First, the series was subjected to the through-time radial GRAPPA technique described in [1] to increase the number of projections per frame by a factor of R_{GRAPPA}. The resulting datasets were then reconstructed to a Nyquist-sampled series using the fast iterative shrinkage-thresholding algorithm for linear inverse problems (FISTA, [2], modified) with discrete gradient sparsification in the temporal domain [3].

Simulation: An in-silico phantom was created to be able to develop and optimize the reconstruction method to establish feasibility (see Fig. 1). Artificial, simplified representations of a cross-section across a mouse thorax was designed on a Cartesian grid based on measured signal-intensities for liver, skeletal muscle, blood and myocardium, respectively (Fig. 1), and multiplied with experimentally determined coil-sensitivity profiles for a four-channel cardiac array. Volumes of the left-ventricular cavity and blood-vessel were simulated, to have an oscillatory motion with a 45° phase shift (ejection fraction: ~66%, heart rate: 500 bpm). After Fourier transforming the phantom images into Cartesian k-spaces, radial projections were calculated using cubic spline interpolation (TR = 1.6ms; 128 readout points; 4, 6 and 8 projections per timeframe). The regularization parameters of FISTA were varied in a wide range to empirically optimize the reconstruction results with respect to the image artifact level, the accuracy of left ventricular volumes and the image sharpness. Different acceleration factors R_{GRAPPA} = 1, 2, 3 and 4 were investigated.

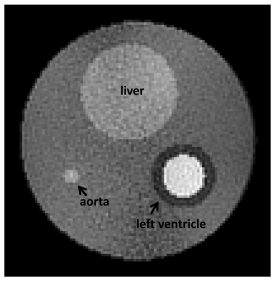

Fig. 1: In-silico phantom.

Validation study: The parameters determined in the simulation stage were used to inform real-time cardiac functional imaging in three mice. A horizontal 9.4T MR system comprising a VNMRS DDR2 console (Agilent, Santa Clara, US) and a 1000 mT/m gradient system and a four-channel cardiac array (Rapid Biomedical, Germany) was used. A linearly segmented radial GE sequence (TE/TR=0.99/1.98ms, FOV=32x32mm, 1mm short-axis slice, matrix size 128x128, flip angle 20°, 50 repetitions) was implemented. The undersampled datasets were then subjected to the reconstruction algorithm described above using R_{GRAPPA} = 4 followed by a denoising using a total variation approach. A fully-sampled, double-gated reference cine was acquired to validate the real time sequence with respect to the image quality and the accuracy of left ventricular volumes.

Results: The best image quality in the simulations was obtained for R_{GRAPPA} = 4 and eight projections per timeframe. After optimizing the regularization of FISTA, a normalized root mean squared error of 16%, a mean loss in spatial image sharpness (endocardial border) of 16% as well as a deviation of 1% from the 'true' left ventricular volume (mean over all phases) were obtained compared to the fully sampled series. The real time images acquired in vivo by applying the optimized setting are depicted in Fig. 2 (temporal resolution: 15.8ms). Ventricular volumes and ejection fraction measured in a mid-ventricular slice from the real time acquisitions agreed well with those from conventional cine data (EDV – 8.9±1.8µl vs 8.8±1.6µl; ESV – 2.69±0.70µl vs. 2.54±0.64µl; SV – 6.2±1.2µl vs. 6.3±1.2µl; EF: 70±3% vs. 71±5%, mean ± SD for real time vs conventional cine, respectively).

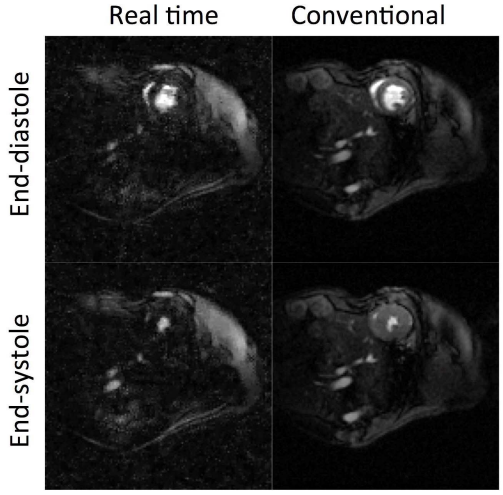

Fig. 2: Results of the in-vivo study.

Discussion & Conclusion: Our study demonstrates that real time imaging of the cardiac function is possible when combining both parallel imaging and compressed sensing. Next steps include the validation of the technique in a larger cohort as well as the investigation of a model with arrhythmic heartbeat.

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References: [1] N. Seiberlich, et al., Magn Reson Med, 65(2):492-505 (2011). [2] A. Beck et al., Siam Journal on Imaging Sciences, 2(1):183-202 (2009). [3] Feng et al. MRM 72:707–717 (2014)