Rapid Real-Time Cardiac MRI Exploiting Synchronized Cardio-Respiratory Sparsity

Li Feng[1], Leon Axel[1], Jian Xu[2], Daniel K Sodickson[1], and Ricardo Otazo[1]
[1] *Bernard and Irene Schwartz Center for Biomedical Imaging, Department of Radiology, New York University, School of Medicine, New York, New York, United States,*
[2] *Siemens Medical Solutions, New York, New York, United States*

Target Audience: Scientists, researchers and clinicians who have interest in rapid cardiac MRI using compressed sensing reconstruction

Introduction: Breath-hold b-SSFP cine imaging is usually considered the gold standard for evaluating myocardial function in MRI [1]. However, the performance of breath-hold cine MRI is degraded in patients with impaired breath-hold capability, due to failure to synchronize cardiac cycles at different respiratory states. In order to minimize the influence from respiration, a deformable registration framework has been incorporated into reconstruction for respiratory motion correction [2,3], but it runs the risk of introducing spatial blurring due to the interpolation errors. Real-time cine MRI is another alternative which allows free-breathing imaging, at the expense of lower spatial resolution [4], and compressed sensing techniques exploiting temporal sparsity have enabled higher spatiotemporal resolutions for real-time cine MRI [5]. However, the superposition of respiratory and cardiac motion limits temporal sparsity. In this work, we propose a novel free-breathing cine MRI framework that sorts and synchronizes cardiac and respiratory motion into two separated dimensions, followed by a joint multicoil compressed sensing reconstruction [6] on the higher dimensional data set, using different sparsity constraints on respiratory and cardiac motion dimensions.

Methods: A HIPAA-compliant and IRB-approved cardiac imaging protocol was performed on two volunteers (males, age=27/30) during consistent free breathing, without any external gating/triggering and preparation, on a 1.5T MRI scanner (Avanto, Siemens). Data were continuously acquired for ~15 seconds in a middle ventricular short axis (SAX) plane, a long axis (LAX) plane and an aortic root (ART) plane, using a 2D b-SSFP pulse sequence with golden-angle radial k-space sampling order. Relevant imaging parameters included: spatial resolution=2x2mm^2, TR/TE=2.8/1.4ms, FA=70^o, slice thickness=8mm and bandwidth=1375Hz/pixel. The temporal evolution of the central k-space position (k_x=k_y=0) in each spoke (green dots, Fig 1a) was used to estimate both cardiac contraction and respiration from coil-elements that were close to the heart and diaphragm, respectively (Fig 1b), as described in [7]. Raw data were then sorted into an expanded dataset containing two dynamic dimensions, for cardiac and respiratory motion states, respectively. As shown in Fig 1b, each rectangular block with a specific color represents an individual cardiac phase from a short "snapshot" period (15 consecutive spokes to produce "real-time" images) in different cardiac cycles. Data are sorted first into a higher dimensional matrix, using the cardiac motion signal (Fig 1c left), followed by a second sorting procedure along the respiratory dimension from expiration to inspiration, using the respiratory motion signal (this operation is performed within each black box in Fig 1c). Reconstruction was performed by minimizing the objective function $\|E\bullet x-y\|_2+\lambda_1\|T_1\bullet x\|_1++\lambda_2\|T_2\bullet x\|_1$, where x is the sorted image to be reconstructed with both cardiac and respiratory dimensions, y is the sampled k-space data in radial k-space and E is the NUFFT [8] operator incorporating the coil sensitivities. T_1 and T_2 are sparsifying transforms (total variation in this work) performed along cardiac and respiratory dimensions, respectively, and λ_1 and λ_1 are the corresponding regularization parameters, which were empirically selected. A 5th order temporal medial filter was used to further remove the residual streaking artifact. For comparison purpose, standard real-time cine reconstructions were also performed, as performed in [9].

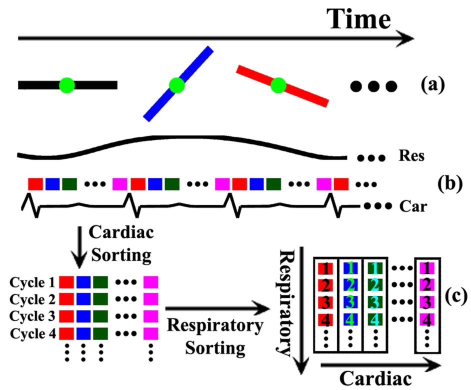

Fig. 1: (a) Continuous data acquisition. (b) Cardiac (Car) / respiratory (Res) motion signals detected from the data itself. (c) Data are first sorted using the cardiac signal and then further sorted using the respiratory signal at each cardiac phase, as indicated by the black boxes

Results: Fig 2 shows reconstructed SAX cardiac cine images at different cardiac phases and respiratory states, with cardio-respiratory synchronization. As shown in the result, the myocardial wall is moving along the respiratory dimension even at the same cardiac phase, which suggests that additional functional information can be obtained by performing the proposed method with cardio-respiratory sorting and synchronization. Fig 3 compares the proposed real-time cine images with synchronized cardiac and respiratory motion/sparsity to the standard real-time cine images reconstruction at end-systolic and end-diastolic phases in different imaging planes. Results with cardio-respiratory synchronization show improved image quality and less residual artifact over standard real-time cine imaging exploiting only one-dimensional temporal sparsity. White arrows in the figure point out some residual artifacts in the standard real-time image reconstruction.

Discussion: Separating cardiac and respiratory motion improves the sparsity of representation and thus acceleration capability and performance for compressed sensing. Instead of incorporating a registration procedure for respiratory motion correction, the proposed approach aims to use joint reconstruction of respiratory motion components to improve the reconstruction in a compressed sensing framework. The proposed approach produces high quality cardiac cine imaging during free-breathing and provides additional functional information, which enables us to investigate the interactions between cardiac and respiratory cycles in their effects on cardiac function. For example, it can be used for evaluating patients with pericardial diseases that may have larger shifts of the interventricular septum with respiration, especially in deep breathing.

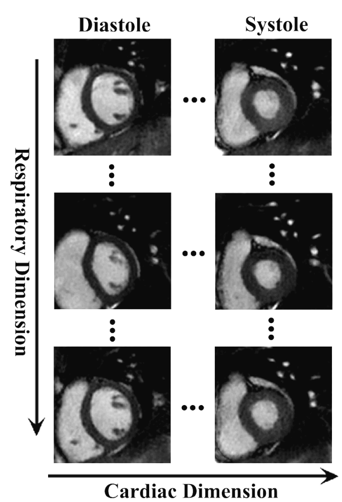

Fig. 2: Different cardiac phases and respiratory states in cardiac cine imaging with cardio-respiratory synchronization.

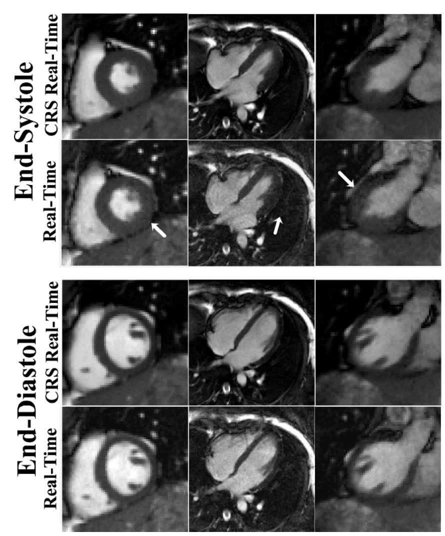

Fig. 3: Comparison of cardiac cine images with cardio-respiratory synchronization to the standard real-time cine imaging at different imaging planes in the volunteer. White arrows point out residual artifacts in the standard real-time image reconstruction
CRS: cardio-respiratory synchronization

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