Motion Corrected Sparse SENSE for highly accelerated Multi Slice cardiac CINE

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Introduction: In MRI, extensive motion during the acquisition (e.g. respiratory motion in cardiac scans) can cause inconsistencies in the k-space data, introducing blurring and ghosting such as motion artefacts in the reconstructed images[1]. Recently, a Motion Corrected-Compressed Sensing (MC-CS) technique[2] had been proposed for free-breathing cardiac MRI. This method benefits from the high acceleration available with CS, and corrects for any arbitrary non-rigid motion in the reconstruction. In comparison with breath-hold (BH) acquisition (~10 sec per slice), MC-CS framework requires longer acquisition time per slice as it requires enough samples in each of the respiratory positions. In this work, for further acceleration of the MR acquisition, we propose to extend the MC-CS framework to parallel MRI and name it 'Motion Corrected Sparse SENSE' (MC-SS). The MC-SS framework performs motion corrected reconstruction from free breathing data without the problems of breath holds and the time taken between them to recover. The total time needed for free breathing acquisition in case of MC-SS framework is the same as the scan duration per slice of a single breath-hold. Prospective multi-slice free-breathing golden radial cardiac MR acquisitions of 2 minutes (10 sec per slice), performed in 5 volunteers and 2 patients with congenital heart disease (CHD), demonstrate the feasibility of MC-SS framework for highly accelerated multi-slice CINE.

Theory: Considering a free breathing CINE acquisition with N cardiac phases and T respiratory positions, the motion corrupted undersampled k-space data ($\mathbf{y_n}$) from a specific coil 'j' for each cardiac phase n=1,2,...,N corresponds to: $\mathbf{y_{j,n}= \Sigma_t A_{t,n} F^s C_j U_{t,n} x_n}$ **(Eq 1),** where $\mathbf{x}_n$ is the motion-corrected image for cardiac phase 'n', $\mathbf{U_{t,n}}$ is the matrix describing the non rigid motion at respiratory position 't' (t=1,2,..,T) for cardiac phase 'n', $\mathbf{C_j}$ is the coil sensitivity from j^{th} coil, $\mathbf{F^s}$ is the 2D spatial Fourier transform, $\mathbf{A_{t,n}}$ is the sampling pattern at the respiratory position 't' for the cardiac phase n, all $\mathbf{A_{t,n}}$'s for a specific cardiac phase 'n' are assumed to be mutually exclusive and $\mathbf{\Sigma}$ is the summation operator. The proposed MC-SS formulation is given as: arg min $_{\mathbf{x}}\| \mathbf{F^t x} \|_1$ s.t. $\mathbf{y_{j,n}= \Sigma_t A_{t,n} F^s C_j U_{t,n} x_n}$ **(Eq 2)**, where $\mathbf{F^t}$ is the Fourier transform along the temporal dimension, $\mathbf{x=[x_1\ x_2\ ...\ x_N]^T}$ and $\|.\|_1$ denotes the l_1 norm. Using the motion information embedded in $\mathbf{U_{t,n}}$, the above formulation finds the sparsest solution in the x-y-f space.

Method: A multi-slice ECG gated free breathing golden angle radial acquisition[3-4] is performed to ensure the k-space sample locations for any specific cardiac phase and respiratory position are mutually exclusive in subsequent R-R intervals allowing flexibility in the reconstruction. Data from different cardiac cycles is retrospectively combined to reconstruct N different cardiac phases. The proposed method can be divided into five steps[2]: a) *Virtual respiratory navigator signals:* Low temporal resolution real time images (one image per cardiac cycle) are reconstructed from free breathing data acquired for each slice. Respiratory navigator signals are generated for each slice by registering real time images with the first image as a reference. b) *Data Binning:* Based on the respiratory navigator signal for each slice, the acquired data is binned into different respiratory positions. c) *Preliminary k-t SS reconstruction:* A preliminary k-t SS reconstruction[5] of all cardiac phases at each respiratory position 't' is done with x-y-f as sparse representation. d) *Motion Estimation:* Each cardiac phase within different respiratory positions is registered to a reference position in the breathing cycle (e.g. end-expiration) using an efficient non-rigid registration algorithm[6] to yield motion fields. e) MC-SS reconstruction: Using the motion matrices $\mathbf{U_{t,n}}$'s constructed from motion parameters, the MC-SS reconstruction is done slice by slice using the formulation in Eq [2].

Experiment: Multislice ECG-gated free breathing golden radial acquisition was performed on Philips 1.5T in 5 volunteers and 2 CHD patients (b-SSFP, TR/TE=4/1.46 ms, matrix size =160x160, FOV: 320x320 mm^2, number of slices: 10-12, slice thickness:8-10 mm, 120-240 radial profiles per cardiac cycle, scan time~2 min). The acquired data were binned into five respiratory positions using adaptive binning with the bin near end-expiration being the reference. The acceleration factor within each bin was 5-8. Twenty cardiac phases were retrospectively reconstructed. For comparison, a multi slice BH acquisition was performed with the same scan time.

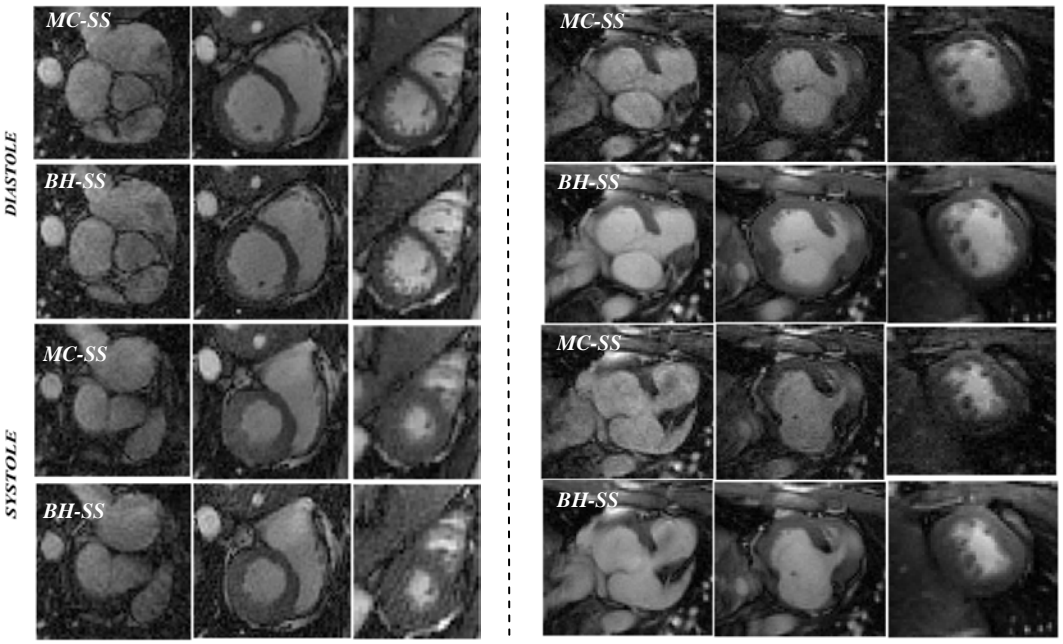

Fig. 1: *MC-SS reconstruction results for a volunteer (three left columns) and a CHD patient with a single ventricle after Fontan operation (three right columns). Three different slices are shown both in the diastolic (upper two rows) and systolic phases (lower two rows). BH-SS reconstruction is also given for reference. From multi-slice acquisition of ~ 2 minutes, MC-SS achieved similar spatial and temporal quality than the BH-SS acquisition of ~4 minutes.*

Results and Discussion: Reconstructed frames in diastole and systole for three different slices are shown in Fig.1 for a volunteer (three left columns) and a CHD patient having only left ventricle (three right columns). MC-SS method corrected for blurring artefacts and resulted in high spatial and temporal quality of the reconstructed images, similar to BH-SS reconstruction. The duration of the free breathing scan in our method is the same as for the BH acquisition. However, there is always a time gap (~10 sec) between BH acquisitions for each slice to allow for the patient recovery between consecutive BH scans. Hence, the overall scan duration for multi-slice BH acquisition will be up to 4 min compared with 2min for our proposed method. Further work will investigate simultaneous reconstruction of all slices using respiratory manifold alignment[7], this should result in increased sparsity in 3D and time, and better reconstruction quality.

References: [1] Batchelor et al, MRM 2005 [2] Usman et al, MRM,2012 [3] Winkelmann et al, IEEE TMI, 2007 [4] Hansen et al, MRM 2011 [5] Otazo et al, MRM 2010 [6] Buerger et al, Medical Image Analysis, 2011 [7] Baumgartner et al, IPMI, 2013