Whole heart motion corrected compressed sensing for 3D free breathing dynamic cardiac MRI

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INTRODUCTION: Multislice 2D CINE MRI is a common approach for assessing cardiac function and anatomy. This approach requires multiple breath-holds, rigorous scan planning and usually suffers from slice-misalignments due to different breathhold position in the multiple acquisitions. To overcome these problems, free-breathing respiratory-gated 3D CINE MRI has been proposed [1-2]. However, these methods require long acquisition times due to low scan efficiency since much of acquired data is rejected and only a fraction of acquired data is used for reconstruction. Recently a Motion Corrected Compressed Sensing (MC-CS) framework [3] has been proposed for free-breathing 2D CINE MRI. MC-CS achieves 100% scan efficiency by combining undersampled CS reconstruction and arbitrary (affine or non-rigid) motion correction directly in the reconstruction. In this work, we propose to extend the MC-CS framework to perform accelerated free-breathing 3D CINE MRI. For data acquisition, we propose to use a 3D Cartesian sampling with spiral profile ordering (CASPR) in the phase-encoding plane, similar to the one used in [4]. One spiral-like interleaf is acquired per cardiac phase in each R-R interval with the angular step between two spiral-like interleaves given by the golden-angle (Fig.1). CASPR allows retrospective respiratory binning, ensuring a quasi-random distribution of samples for any cardiac phase at any respiratory position as required for CS reconstruction. The usefulness of this framework is demonstrated in simulations where a respiratory motion corrected cardiac cycle is reconstructed. Initial results in in-vivo whole-heart free breathing CINE data show the feasibility of the proposed approach.

THEORY: Considering a free breathing CINE acquisition with N cardiac phases and T respiratory positions, the motion corrupted undersampled k-space data ($\mathbf{y_n}$) for each 3D cardiac phase (n = 1,2,...,N) corresponds to: $\mathbf{y_n = \Sigma_t A_{t,n} F^s U_{t,n} x_n}$ **(Eq 1),** where $\mathbf{x_n}$ is the 3D motion-corrected volume for cardiac phase 'n', $\mathbf{U_{t,n}}$ is the matrix describing the 3D non-rigid motion at respiratory position 't' (t = 1,2,..,T) for cardiac phase 'n', $\mathbf{F^s}$ is the spatial Fourier transform and $\mathbf{A_{t,n}}$ is the 3D undersampling pattern at the respiratory position 't' for the cardiac phase n.

The 3D MC-CS formulation is given as: $\min_{\mathbf{x}} \| \mathbf{F^t x} \|_1$ s.t. $\mathbf{y_n = \Sigma_t A_{t,n} F^s U_{t,n} x_n}$ **(Eq 2)**, where $\mathbf{F^t}$ is the Fourier transform along the temporal dimension, $\mathbf{x=[\, x_1\, x_2 \ldots x_N]^T}$ 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-z-f space.

METHOD: An ECG-gated 3D CASPR acquisition is implemented to acquire data in each R-R interval along spiral-like interleaves in phase encoding ky-kz plane. N spiral interleaves per R-R interval are used to avoid asymmetric sampling in k-space (Fig.1). This phase encoding scheme leads to quasi-uniform random distribution of samples across the k-space for any cardiac phase 'n' at any respiratory position 't'. After acquisition of a number of interleaves that populate full k-space, a shift in the initial angle is introduced to avoid overlapped samples in the final reconstruction. Respiratory signal for binning is obtained from a 1D diaphragmatic navigator. Data from different cardiac cycles are retrospectively combined to reconstruct N different cardiac phases. The proposed 3D MC-CS framework can be divided into four steps: *1)* Data acquired with CASPR scheme is binned according to the respiratory signal, *2)* Data within each bin is reconstructed with 3D CS, *3)* These reconstructed respiratory resolved volumes are registered to a reference breathing position (e.g. end-expiration) using an efficient non-rigid registration algorithm [5] to yield 3D motion fields. *4)* Using the motion matrices $\mathbf{U_{t,n}}$'s constructed from motion parameters, the 3D MC-CS reconstruction is done using the formulation in Eq. (2).

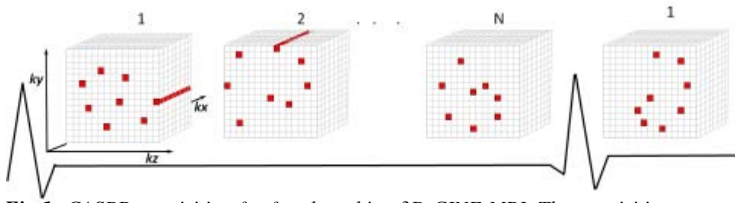

Fig 1: *CASPR acquisition for free breathing 3D CINE MRI. The acquisition ensures quasi-random distribution of samples across 3D k-space*

EXPERIMENT: *a) Simulation:* Motion corrupted 3D data was simulated using CASPR trajectory from breath-held multi-slice CINE MRI acquired on 1.5T scanner (Achieva, Philips Healthcare) using a b-SSFP acquisition (TR/TE=3/1.5 ms, matrix size: 192x192x20, 20 cardiac phases, FOV: 384x384x160 mm^3, scan time = 19 sec per slice). Non-rigid transformations corresponding to different 3D radial and angular deformations were generated for two respiratory positions. The reference respiratory position was considered to be the end-expiration at which the breath-held data was obtained. A respiratory signal, obtained from a prolonged in-vivo free breathing cardiac scan, was employed to simulate the 3D sampling of each deformed cardiac phase sequence at each respiratory position. For undersampling, the number of heartbeats was decreased such that data for each cardiac phase at a specific respiratory position was reduced by acceleration factor of 3 to 8.

b) In-vivo Experiment: An ECG-gated whole-heart free breathing CASPR acquisition was performed on a 3T scanner (Achieva, Philips Healthcare) in two volunteers using a b-SSFP sequence (TR/TE=3.2/1.6 ms, matrix size =152x152x20, FOV: 304x304x120 mm^3, scan time= 4.6 min). The acquired data was binned into three regularly spaced respiratory positions (bin width: 5mm) with regard to the displacement of diaphragm at the lung-liver interface, with the bin near end-expiration being the reference. Fourteen cardiac phases were retrospectively reconstructed.

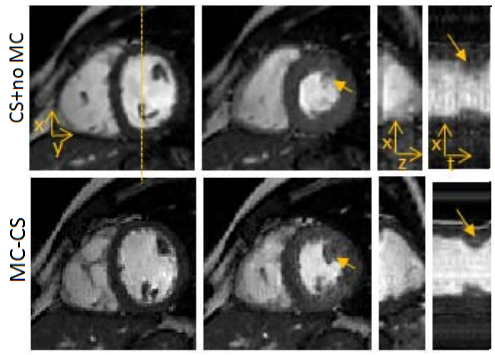

Fig 2: Simulation results from undersampled non-rigid motion corrupted data: *3D reconstructed cardiac frames obtained from CS reconstruction without (CS+ no MC) and with motion correction (MC-CS). Profiles corresponding to temporal variation of pixel intensities (along yellow dotted line) are shown in last column.*

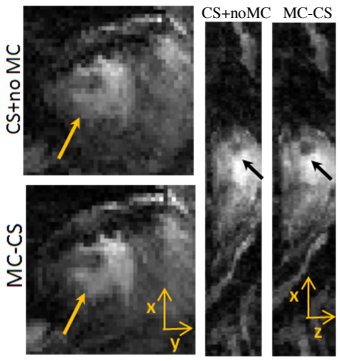

Fig 3: In-vivo 3D free breathing CINE MRI: *3D reconstructed cardiac frames without (*CS+no MC*) and with motion correction (*MC-CS*). MC-CS images have better delineation of the boundary of myocardium compared to* CS+no MC.

RESULTS: *a) Simulation:* CS reconstruction results without (CS+no MC) and with motion correction (MC-CS) for acceleration factor of 6 in each motion state are shown in Fig.2. Two cardiac frames and a temporal profile (across left ventricle) are shown for each reconstruction. Strong blurring artefacts are evident in the CS+ no MC reconstruction. MC-CS corrected for non-rigid motion and achieved the same quality as for breath-held volumes (not-shown here).

b) In-vivo Experiment: Reconstructed cardiac frames without (CS+no MC) and with motion correction (MC-CS) are shown in Fig. 3. MC-CS method corrected for blurring artefacts and resulted in better quality of the reconstructed images.

DISCUSSION: A 3D motion corrected compressed sensing framework that allows for simultaneous motion correction and undersampled reconstruction has been presented. This approach uses 3D CASPR acquisition that is computationally efficient, since iterative reconstruction does not require gridding/re-gridding steps. Feasibility of the proposed method was shown in simulations and in-vivo 3D CINE MRI. MC-CS will be combined with parallel imaging and better 3D CINE contrast will be investigated in future work to further improve the performance of the proposed method.

REFERENCES: [1] Larson et al, MRM 2004, [2] Uribe et al, MRM 2007 [2] Usman et al, MRM 2012 [3] Doneva et al, ISMRM 2011 [4] Kellman et al, MRM, 2008 [5] Buerger et al, Med IA, 2011