

Combination of Compressed Sensing and Parallel Imaging for Highly-Accelerated 3D First-Pass Cardiac Perfusion MRI

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INTRODUCTION: Whole-heart coverage per heartbeat is desirable for first-pass cardiac perfusion MRI studies. 3D imaging offers a particularly appealing alternative to the SNR and volumetric coverage limitations of multi-slice 2D techniques [1-2]. However, 3D approaches are more susceptible to cardiac motion artifacts due to their longer acquisition time. Parallel imaging using many-element coil arrays can be used to substantially accelerate 3D acquisitions. At last year's ISMRM meeting, whole-heart coverage per heartbeat was reported using a 32-element array with 8-fold acceleration [3]. However, further acceleration is required to achieve an adequate spatial and temporal resolution for clinical studies. An alternative acceleration technique for perfusion MRI is compressed sensing (CS) [4]. CS exploits spatial and temporal correlations, resulting in sparsity of image series content, to achieve high levels of undersampling without loss of image information. We have recently presented a combination of CS and parallel imaging (PI) to increase the acceleration rate for 2D perfusion MRI by exploiting the properties of joint multicoil sparsity [5]. In this work, we extend our previously developed combination of CS and PI to 3D perfusion MRI to achieve whole-heart coverage per heartbeat with increased spatial and temporal resolution using a 32-element coil array with a net acceleration factor of 16.

METHODS: First-pass 3D cardiac perfusion MRI was performed on two healthy volunteers with 0.1 mmol/kg of Gd-DTPA (Magnevist). A 3D saturation-recovery TurboFLASH pulse sequence was modified to include user defined phase-encoding, partition-encoding and time (k_y - k_z - t) sampling pattern (Fig. 1), and this pulse sequence was implemented on a 1.5T scanner (Siemens, Avanto) equipped with a 32-element cardiac coil array (In Vivo). An axial acquisition was performed in mid-diastole to reduce sensitivity to cardiac motion. The relevant imaging parameters include: FOV = 340x340x100 mm³, image matrix = 128x128x16, spatial resolution = 2.65x2.65x6.25 mm³, flip angle = 10°, TE/TR = 0.9/2.3 ms, temporal resolution = 294 ms (complete volume), repetitions = 40. Low spatial resolution coil sensitivity data were acquired during the first heartbeat of the dynamic imaging, with flip angle = 5° and without the saturation pulse. Acceleration was accomplished using k_y - k_z - t random undersampling in which a different variable density undersampling pattern along k_y - k_z was used for each temporal volume to produce the required incoherent artifacts in the sparse x - y - z - f domain.

Image reconstruction was performed offline using a combination of compressed sensing and SENSE [5], where joint sparsity is enforced on the multicoil combination rather than on each coil separately, in order to exploit oversampling and incoherence along the coil dimension. The acquisition model for each coil is given by $\mathbf{y}_i = \mathbf{F}_{x,y,z} \mathbf{S}_i \mathbf{d}$, where \mathbf{y}_i is the undersampled data, $\mathbf{F}_{x,y,z}$ is the Fourier transform along x , y and z , \mathbf{S}_i represents the coil sensitivities and \mathbf{d} is the dynamic image to be reconstructed. The multicoil acquisition model is formulated by concatenating the individual models into $\mathbf{y} = \mathbf{E} \mathbf{d}$. A Fourier transform

along the time dimension (\mathbf{F}_t) and finite differences along the spatial dimensions ($\Delta_{x,y,z}$) were used as sparsifying transforms. The joint compressed sensing reconstruction for each slice using l_1 -norm minimization is given by: $\hat{\mathbf{d}} = \arg \min_{\mathbf{d}} \left\{ \|\mathbf{E} \mathbf{d} - \mathbf{y}\|_2^2 + \lambda_t \|\mathbf{F}_t \mathbf{d}\|_1 + \lambda_s \|\Delta_{x,y,z} \mathbf{d}\|_1 \right\}$, where λ_t and λ_s are

weighting parameters that control the balance between sparsity along the time dimension and the spatial dimensions respectively, and parallel imaging data consistency (left-hand term).

RESULTS: Fig. 2 shows reconstructed images for the complete volume (16 partitions) at peak blood and peak myocardial wall enhancement phases of the *in vivo* breath-held experiment with true 16-fold acceleration. The reconstructed images covered the complete heart with adequate blood image quality.

DISCUSSION: Higher accelerations rates were feasible with 3D than with 2D perfusion imaging due to increased sparsity and incoherence provided by the higher dimensionality of the data, multi-dimensional coil-sensitivity encoding, and increased baseline SNR afforded by the volumetric acquisition. This acceleration was employed to provide whole-heart volumetric coverage with adequate spatial and temporal resolution. Future work includes exploring non-separable spatial-temporal sparsifying transforms, arrays with larger number of elements, and implementation at 3T, in order to achieve even higher acceleration rates.

GRANT SPONSOR: NIH R01-EB000447, AHA 0730143N.

REFERENCES: [1] Kellman P et al. ISMRM 2004; 310. [2] Shin T et al. JCMR. 2008; 10:57-66. [3] Xu J et al. ISMRM 2009; 765. [4] Lustig M et al. MRM 2007; 58:1182-95. [5] Otazo R et al. ISMRM 2009; 378.

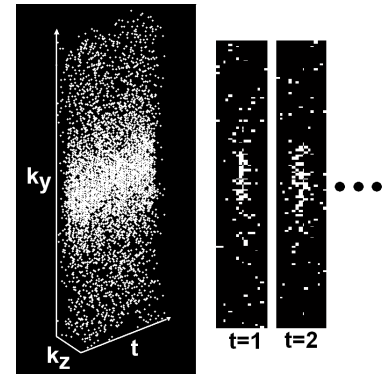


Fig. 1: k_y - k_z - t sampling pattern with 16-fold acceleration (white: sampled). A different k_y - k_z random sampling pattern is used for each temporal frame (t).

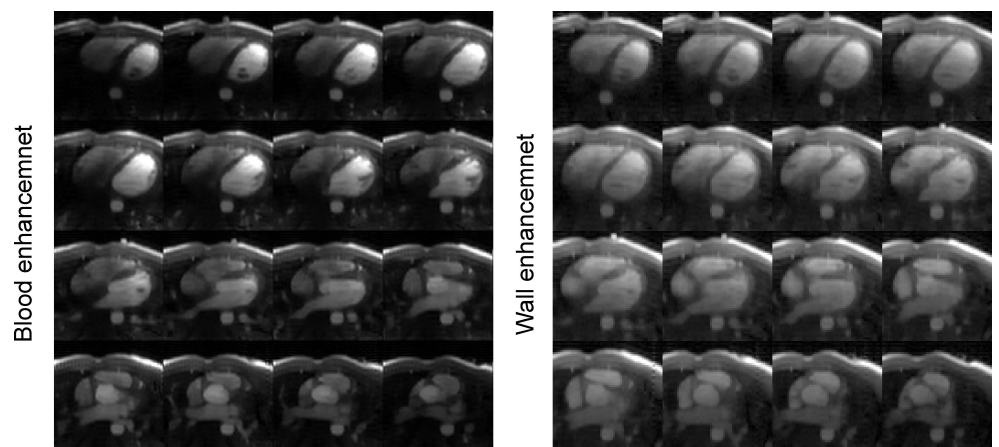


Fig. 2: Breath-held, 16-fold accelerated 3D first-pass perfusion images on a healthy volunteer.