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

L. Feng[1,2], J. Xu[3,4], D. Kim[2], L. Axel[2], D. K. Sodickson[2], and R. Otazo[2]

[1]Sackler Institute of Graduate Biomedical Sciences, New York University School of Medicine, New York, NY, United States, [2]Department of Radiology, New York University School of Medicine, New York, NY, United States, [3]Siemens Medical Solutions USA, [4]Polytechnic Institute of NYU, Brooklyn, NY, United States

Introduction: First-pass myocardial perfusion MRI is a promising and noninvasive technique for evaluation of ischemic heart disease. 3D whole-heart coverage per heartbeat is desirable for clinical perfusion studies to overcome the contrast-to-noise ratio (CNR) and volumetric coverage limitations associated with multi-slice 2D perfusion MRI studies [1-2]. Highly accelerated imaging is a necessary for 3D perfusion MRI to achieve clinically acceptable spatial and temporal resolutions. Whole-heart coverage per heartbeat was achieved by TGRAPPA parallel imaging with 8-fold acceleration using a 32-element coil array [3]. Higher accelerations were feasible by combining compressed sensing (CS) [4] and parallel imaging (PI), where the temporal sparsity of the perfusion time-series and coil sensitivity encoding were jointly exploited to obtain a 16-fold acceleration rate (R) [5]. While these developments represented important advances in the direction of 3D perfusion MRI, higher accelerations are still needed to meet clinical requirements. Another complementary method for reducing acquisition time is partial Fourier (PF) imaging, which was recently combined with CS to increase acceleration factor [6]. In this work, we combine CS, PI and PF to further accelerate 3D cardiac perfusion MRI and enable whole-heart coverage with previously inaccessible combinations of temporal and spatial resolution.

Methods: First-pass 3D cardiac perfusion MRI was performed on a healthy volunteer 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 with R = 24 (Fig. 1). The accelerated sampling pattern uses a combination of (a) different k_y-k_z pseudo-random undersampling pattern for each time point to produce the required incoherent artifacts in the sparse x-y-z-f domain and (b) 3/4 partial Fourier sampling in k_y and k_z directions. For comparison, a TurboFLASH pulse sequence using TGRAPPA was also used in the same subject with R=8 (for convenience, the former method is referred to as CS-PI-PF and the latter is referred to as TGRAPPA). Both pulse sequences were implemented on a 3T scanner (Siemens, Verio) 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 for both sequences are: FOV = 400x400 mm, flip angle = 10°, receiver bandwidth = 1532 Hz/pixel, TE/TR = 0.9/2.3 ms, repetitions = 40. For CS-PI-PF, acquisition matrix = 192x192x8 and temporal resolution = 147 ms. For TGRAPPA, acquisition matrix = 128x128x8 (3/4 partial Fourier was used in k_z direction) and temporal resolution = 220 ms. In CS-PI-PF, low spatial resolution coil sensitivity data were acquired during the first heartbeat before dynamic imaging without the saturation pulse. TGRAPPA image reconstruction was performed on-line using commercially available reconstruction software. CS-PI-PF image reconstruction was performed offline using customized software developed in Matlab (Mathworks, MA) by 3 steps using temporal fast Fourier transform (FFT) as sparsifying transform. In the first step, joint CS-PI reconstruction [5] was used to reconstruct the 3/4 asymmetric k-space region covered by partial Fourier sampling (matrix=192x144x6). In the next step, the central symmetric part of the reconstructed k-space data in the first step, as shown by the red box in Fig. 2, was used to produce a low-resolution phase map. In the third step, partial Fourier reconstruction was performed for each time point of the asymmetric 3/4 k-space data reconstructed in the first step, using a two-dimensional POCS algorithm with phase correction [7-8].

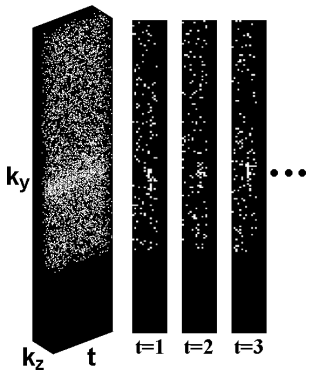

Fig. 1: k_y-k_z-t sampling pattern with R=24 using a combination of different random undersampling patterns for each time point with 3/4 partial Fourier coverage at all times.

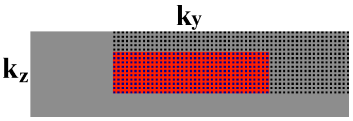

Fig. 2: Reconstructed k_y-k_z area after first step of CS-PI-PF. The central portion of k-space data (shown in red) was used to generate a low-resolution phase map.

Results: Fig. 3 shows representative images for the complete volume (8 partitions) at peak blood (left) and peak myocardial wall (right) enhancement phases with CS-PI-PF (top rows, R=24) and TGRAPPA (bottom rows, R=8). Myocardial contours are cropped and zoomed in 4th partition to show the increased resolution in CS-PI-PF, as indicated by the red boxes of Fig. 3. The higher acceleration of CS-PI-PF resulted in improved image quality compared to TGRAPPA. Note that CS-PI-PF reconstruction resulted in lower noise, which is in part due to the non-linear regularization performed by compressed sensing.

Discussion: High accelerations of 3D perfusion MRI are feasible due to image sparsity and incoherence provided by the high dimensionality of the data. By combining CS and PI with PF, the acceleration rate can be further increased to achieve higher spatiotemporal resolution and CNR. Future work includes exploration of non-separable 4D spatial-temporal sparsifying transforms, arrays with larger number of elements and parallel computing to accelerate image reconstruction.

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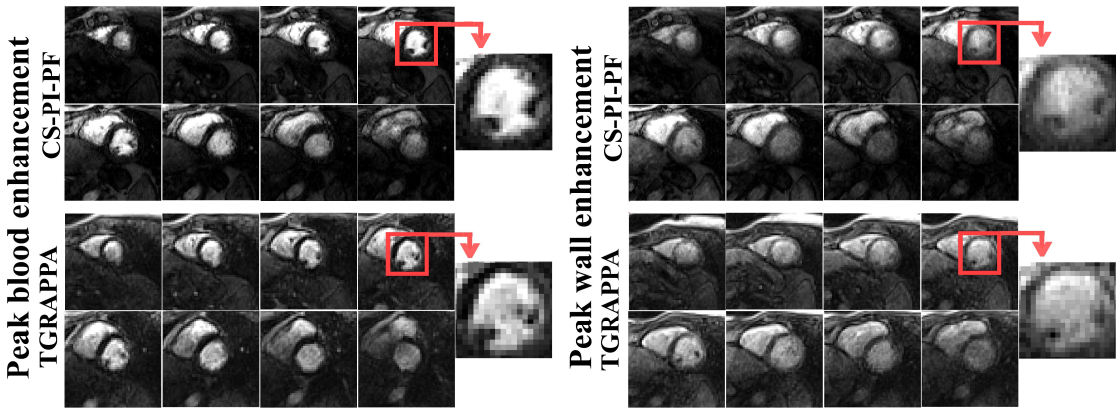

Fig. 3: Breath-held, accelerated 3D first-pass perfusion images of a healthy volunteer: (top rows) CS-PI-PF (R=24) and (bottom rows) TGRAPPA (R=8). Myocardial contours are zoomed in 4th partition in the right side, as indicated by the red boxes.

Reference: [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 2010; 344. [6] Doneva M et al. ISMRM2010; 4851. [7] Xu Y et al. JMRI 2001; 14:628–635. [8] Singh R et al. JMRI 2004 9:645–649.