Highly-Accelerated First-Pass Cardiac Perfusion MRI Using Compressed Sensing and Parallel Imaging

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INTRODUCTION: First-pass cardiac perfusion MRI is a promising modality for the assessment of coronary artery disease. Recently developed dynamic parallel imaging techniques, such as k-t SENSE [1] and k-t GRAPPA [2], can be used to perform up to 10-fold accelerated perfusion imaging by exploiting the difference in coil sensitivities and spatio-temporal correlations. Such techniques can be used to increase the data acquisition efficiency, which can then be utilized to increase the spatio-temporal resolution and/or spatial coverage. However, these k-t parallel imaging techniques require dynamic training data which reduces the effective acceleration rate. An alternative technique which does not require training data is compressed sensing [3]. Four-fold accelerated cardiac perfusion MRI has been demonstrated with a compressed sensing technique exploiting the sparsity of the dynamic image set in x-f space and employing k-t random undersampling [4]. In this work, a joint reconstruction approach, named k-t Parallel-Sparse, is developed to combine compressed sensing and parallel imaging for highly (> 6-fold) accelerated cardiac perfusion MRI.

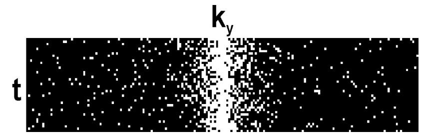

Fig. 1: ky-t sampling pattern for R=8 (white: sampled point).

METHODS: Cardiac perfusion MRI was performed on a healthy volunteer with 0.1 mmol/kg of Gd-DTPA (Magnevist). A modified TurboFLASH pulse sequence with user defined phase-encoding and time (k_y-t) sampling pattern (Fig. 1) was employed on a whole-body 3T scanner (Siemens; Tim Trio) equipped with a 12-element coil array. The relevant imaging parameters include: FOV = 320 x 320 mm, image matrix = 192 x 192, slice thickness = 8 mm, flip angle = 10°, TE/TR = 1.3/2.5 ms, BW = 1000 Hz/pixel, RF pulse train saturation pulse [5], saturation recovery time delay (TD) = 10 ms, repetitions = 40. Low spatial resolution coil sensitivity maps were acquired during the first heartbeat of the dynamic imaging using a linear k-space reordering with full Nyquist sampling. Acceleration was accomplished using k_y-t random undersampling in which a different variable density undersampling pattern along k_y was used at each time point to produce the required incoherent artifacts in the sparse y-f domain (Fig. 1). Sampling more densely at the center of k_y–space increases incoherence and provides a better starting point for reconstruction than purely random sampling [3]. The k_y sampling was performed using a "reverse centric" phase reordering, in order to increase the contrast-to-noise ratio at the expense of slight blurring in the k_y direction [6]. Breath-hold measurements with high acceleration factors of R = 8 (allowing 10 acquired slices per heartbeat) and R = 12 (allowing 13 slices per heartbeat) were performed. A free-breathing acquisition with R=8 was also performed to evaluate the sensitivity to respiratory motion. The contrast washout time was 20 min between the three separate contrast-enhanced MRI acquisitions.

k-t Parallel-Sparse reconstruction was performed by adding the coil sensitivities explicitly into the compressed sensing approach for a single coil proposed in [3] and by enforcing sparsity on the single combined image rather than on each coil image. The acquisition model for each coil is given by $\mathbf{m}_i = \mathbf{F}\mathbf{S}_i\mathbf{d}$, where $\mathbf{m}_i$ is the undersampled dynamic image in x-f space, $\mathbf{F}$ is the undersampled Fourier transform, $\mathbf{S}_i$ is the coil sensitivity and $\mathbf{d}$ is the dynamic image to be reconstructed in x-f space. The complete acquisition model is formulated by concatenating the individual models into $\mathbf{m} = \mathbf{E}\mathbf{d}$. The reconstructed image is given by the $\mathbf{d}$ that minimizes $\|\mathbf{E}\mathbf{d}-\mathbf{m}\|_2^2 + \lambda\|\mathbf{d}\|_1$, where $\|\mathbf{x}\|_2 = \left(\sum |x_i|^2\right)^{1/2}$ is the L_2-norm, $\|\mathbf{x}\|_1 = \sum |x_i|$ is the L_1-norm and λ is a regularization parameter that controls the tradeoff between parallel imaging data consistency (left term) and sparsity (right term). The reconstruction was implemented with a non-linear conjugate gradient approach [3] with λ=1 using the zero-filled dynamic image normalized to 1 as starting point. The final result in x-t space is obtaining by applying an inverse temporal Fourier transform to $\mathbf{d}$. Signal intensity time courses were evaluated on the reconstructed dynamic images using two different region of interest (ROI)'s for the blood and the myocardial wall.

RESULTS: Figure 2 shows representative images of the same volunteer at peak blood and myocardial wall enhancement for R = 8 and R = 12. Compared with the 8-fold accelerated data, the 12-fold accelerated data exhibited more incoherent artifacts (pseudo-noise) and blurring, due to the higher level of interference in the sparse x-f domain which makes it more difficult to recover high spatial and temporal frequency components. Fig. 3 shows the signal-time curves of the blood and wall for R=8 and R=12. As expected, the R=12 curve exhibited more noise in the myocardial wall signal-time curve. The 8-fold accelerated data acquired with free breathing did not show respiratory motion artifacts (Fig. 4).

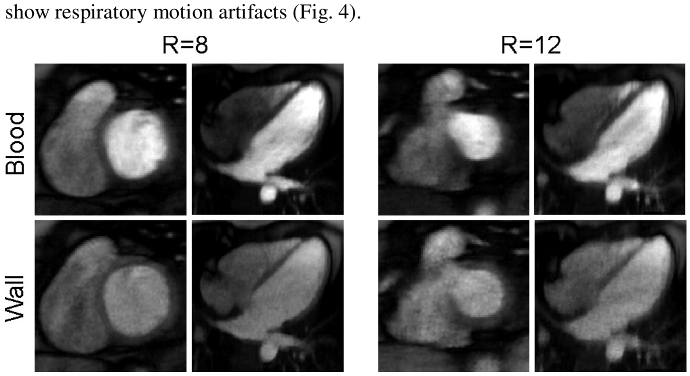

Fig. 2: Images at peak blood and myocardial wall enhancement in a basal short-axis view and a 4-chamber view.

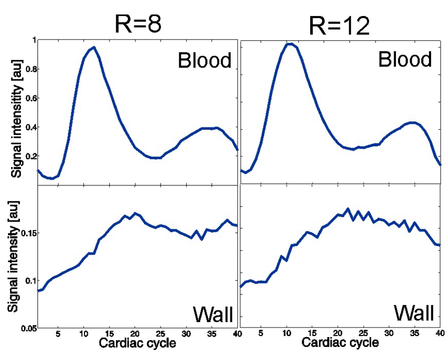

Fig. 3: Signal-time curves of the blood and the myocardial wall.

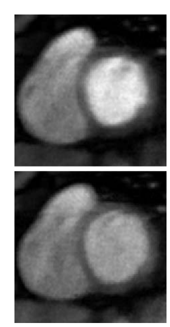

Fig. 4: 8-fold accelerated data acquired with free-breathing.

DISCUSSION: The proposed k-t Parallel-Sparse method allows for high accelerations in first-pass cardiac perfusion imaging using a joint reconstruction approach that combines compressed sensing and parallel imaging. The advantages of k-t Parallel-Sparse over other k-t techniques is that it does not require dynamic training data and that it is relatively insensitive to respiratory motion. The maximum acceleration available in the proposed method is limited by the sparsity of the image and the number of receiver coils. This work demonstrates feasibility of the k-t Parallel-Sparse method; more extensive comparative image quality evaluations are now underway. Tailored sparsifying transforms which jointly weight spatial and temporal dimensions may further improve the performance in cardiac perfusion MRI, as will the use of larger numbers of coil array elements and, potentially, three-dimensional acquisitions.

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