Myocardial Perfusion Imaging: Improved Image Reconstruction using Respiratory Motion Corrected (MOCO) SPIRiT

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Introduction Myocardial perfusion imaging with saturation recovery has insufficient SNR due to the demand for high spatio-temporal resolution. To improve the quality of free-breathing myocardial perfusion imaging, we propose to extend the SPIRIT reconstruction [1] by incorporating non-rigid respiratory motion correction (MOCO). With MOCO, it is possible to employ spatio-temporal regularization for better image quality while retaining the dynamic information (i.e. preserve the fidelity of time intensity curves). The improved SNR may be used to support higher spatial resolution which is the key to minimize dark rim artifacts. Unlike k-t methods without MOCO that are susceptible to respiratory motion, the MOCO-SPIRiT allows free-breathing. We compare this new algorithm with TGRAPPA [2] and L1SPIRiT [3], and characterize the spatio-temporal point spread function using an impulse approach [4].

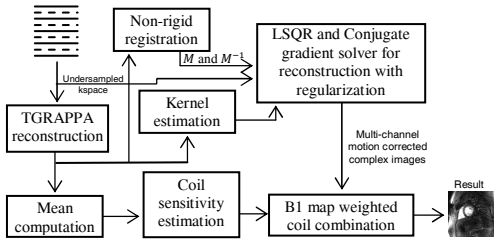

Figure 1. Schematic diagram of proposed reconstruction scheme.

Material and Methods ***MOCO-SPIRiT:*** As shown in Fig. 1, all temporally interleaved k-space frames were averaged to generate auto-calibration (ACS) signals and TGRAPPA was first performed. The resulting images were fed into the inverse-consistent non-rigid registration step to compute the forward and backward deformation fields. The consecutive perfusion motion correction scheme proposed in [5] is applied here to handle the significant intensity changes during the contrast uptake. Given the undersampled kspace $\boldsymbol{a}$ acquired with free-breathing, the MOCO-SPIRiT aims to reconstruct the motion-corrected multi-channel images $\boldsymbol{x}^*$ by solving the following optimization problem:

$$\boldsymbol{x}^* = \min_{\boldsymbol{x}}\{\|(\boldsymbol{G}-\boldsymbol{I})\boldsymbol{F}\boldsymbol{M}^{-1}\boldsymbol{x}\|_2 + \lambda\cdot\|\boldsymbol{\psi}\boldsymbol{C}^H\boldsymbol{x}\|_1 + \beta\cdot\|\boldsymbol{D}\boldsymbol{F}\boldsymbol{M}^{-1}\boldsymbol{x}-\boldsymbol{a}\|_2\}$$

Here $\boldsymbol{x}$ is $\boldsymbol{N_c}$ channels of unknown motion corrected image series. $\boldsymbol{G}$ is the SPIRiT calibration kernels. $\boldsymbol{M}$ and $\boldsymbol{M^{-1}}$ are computed from the inverse-consistent non-rigid registration step, representing the forward and backward motion correction operator. $\boldsymbol{F}$ is the Fourier transform and $\boldsymbol{C}$ is the coil sensitivity. $\boldsymbol{C^H x}$ represents the coil combination, converting the multi-channel complex image to the coil combined image which is then fed into the wavelet transform $\boldsymbol{\psi}$. The first term here is the self-consistent constraint. The second term is the L1 spatio-temporal regularization and the third enforces the data fidelity. ***Phantom study:*** To quantify the performance of proposed algorithm and justify the parameter selection, a perfusion digital phantom is generated using the NURBS-based Cardiac-Torso (NCAT) software [6] with the following parameters: image matrix 256×256, resolution 1.563×1.563mm^2, heart rate 60bpm, one image per heart beat, simulated period 45s, respiratory period 6s, maximal diaphragm motion 1cm. The time-intensity curves of myocardium, left and right ventricular are taken from a real perfusion dataset. Noise is added to the phantom, making the peak myocardial SNR of the phantom match a typical in-vivo acquisition. To reasonably select algorithm parameters $\boldsymbol{\lambda}$ and $\boldsymbol{\beta}$, the local point spread function and related noise equivalent bandwidth ratio (BWratio) is computed using the impulse method [4]. For all in vivo and phantom tests, $\boldsymbol{\lambda}$ and $\boldsymbol{\beta}$ are fixed as 1.0 and 0.02, leading to a BWratio at the endo boundary being ~0.75 in the phantom study (Fig. 2). ***In-vivo study:*** 14 patients (8 males; age 46.9–69.9yrs) underwent free-breathing perfusion examinations with written consent. For each patient, three short-axis slices were acquired for both rest and pharmaceutical stress conditions, leading to 84 perfusion series. Typical imaging parameters are: TurboFlash readout, acquired image matrix 192×120, resolution 1.875×2.25 mm^2, R=2 time-interleaved undersampling of k-space. SNR is estimated for both MOCO-SPIRiT and TGRAPPA images in a region-of-interest (ROI) selected from healthy myocardium. The TGRAPPA results are retrospectively motion corrected before measuring SNR.

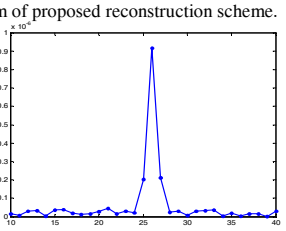

Figure 2. Measured temporal point spread function. The noise equivalent bandwidth ratio is 0.76.

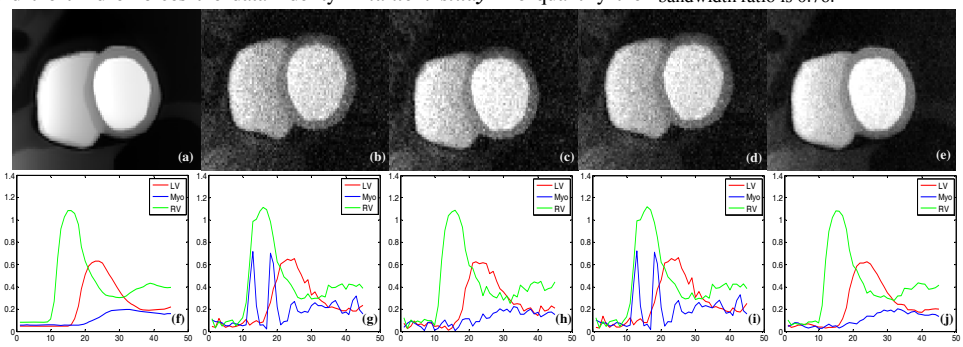

Figure 3. Reconstruction results of perfusion phantom. (a,f) Ground-truth, (b.g) TGRAPPA reconstruction, (c,h) TGRAPPA with retrospective motion correction, (d,i) L1SPIRiT, (e,j) MOCO-SPIRiT. Time intensity curves from RV(green), LV(blue) and myocardium(red) show the better performance of MOCO-SPIRiT by correcting myocardial motion and improving SNR.

Results All results were visually inspected to ensure no discernible artifacts are generated by the proposed reconstruction. Compared to the TGRAPPA (peak myocardium SNR 4.36±1.22), the proposed method leads to significant SNR gain (7.42±1.93, P<1e-5). Furthermore, while the L1SPIRIT with the same spatio - temporal regularization improves the SNR, it leads to noticeable cross-talk between frames (Fig. 4c) due to respiratory motion. This artifact is well removed by the proposed method.

Conclusions A novel iterative reconstruction algorithm, MOCO-SPIRiT is proposed and applied to the myocardial perfusion imaging. The novelty lies on the combination of inverse-consistent non-rigid registration into the reconstruction, enabling free-breathing perfusion acquisition with improved spatial resolution. Experiments show MOCO-SPIRiT leads to significantly improved SNR over TGRAPPA and fewer artifacts under the free-breathing acquisition condition over L1SPIRiT. While current in-vivo tests were performed with R=2 acceleration, the method can well be applied with higher acceleration for better spatial/temporal resolution.

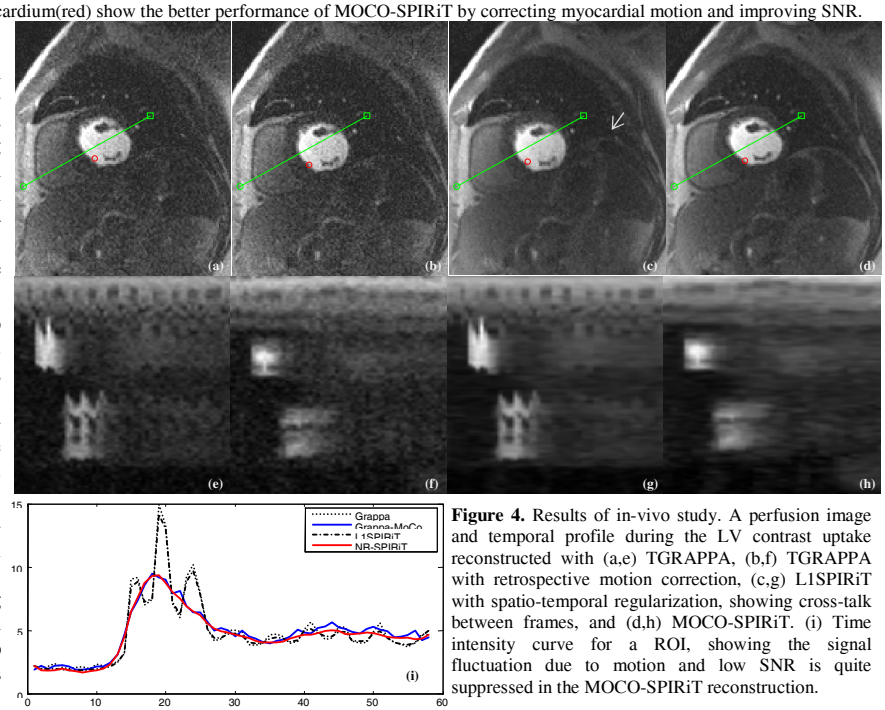

Figure 4. Results of in-vivo study. A perfusion image and temporal profile during the LV contrast uptake reconstructed with (a,e) TGRAPPA, (b,f) TGRAPPA with retrospective motion correction, (c,g) L1SPIRiT with spatio-temporal regularization, showing cross-talk between frames, and (d,h) MOCO-SPIRiT. (i) Time intensity curve for a ROI, showing the signal fluctuation due to motion and low SNR is quite suppressed in the MOCO-SPIRiT reconstruction.

References [1] Lustig M, et al., MRM 64:457-471 (2010) [2] Breuer FA, et al., MRM 53(4):981-985 (2005) [3] Lustig M, et al., ISMRM 334 (2009) [4] Wech T, et al., Med. Phys. 39 (7):4328-4338 (2012) [5] Xue H, et al., MICCAI 741-749 (2009) [6] http://dmip.rad.jhmi.edu/people/faculty/Paul/Segars_research.htm#NCAT