Self Consistent Parallel Imaging with Temporal Sensitivity Estimation (TSPIRIT): Application to improve Real-time Exercise Stress Cardiac Cine and Perfusion Imaging

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Introduction Myocardial perfusion and wall motion can now be assessed using CMR immediately following treadmill exercise which provides more information to link physical activity to symptoms and ischemia, compared to pharmacologic stress imaging [1]. Given that exercise stress induced perfusion deficits and wall motion abnormalities rapidly fade after cessation of exercise, imaging must be completed as quickly as possible. Additionally, shortness of breath following exercise precludes the use of segmented k-space acquisitions making real-time imaging the only practical choice for post-exercise cardiac imaging. While this eliminates the needs for ECG triggering and breath-holding, signal-noise-ratio (SNR) and temporal/spatial resolution are typically sacrificed. Image degradation can be more severe for post-exercise cine due to rapid heart rate and exaggerated breathing. To improve the quality of exercise stress imaging, we propose to utilize the recently proposed SPIRIT reconstruction technique [2] by incorporating improved temporal sensitivity estimation (TSPIRIT) and spatial regularization, aiming to achieve significant better SNR than the conventional temporal GRAPPA reconstruction (TGRAPPA) [3]. Compared to the regularized SPIRIT reconstruction with averaged-all auto-calibration (ACS) signals, the proposed method significantly suppresses the ghosting artifacts caused by rapid breathing.

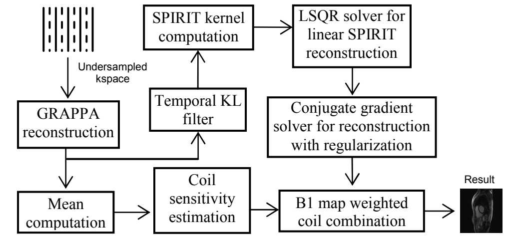

Figure 1. Schematic diagram of proposed reconstruction scheme.

Material and Methods ***Cine imaging:*** 17 healthy volunteers (10 males; age 21.6−48.7yrs) underwent free-breathing real-time exercise stress cine examinations after having given written consent. An MR compatible treadmill system was utilized [1] together with a 1.5T scanner (Avanto, Siemens) and a 32-channel coil (Rapid MRI). Three slices (one short-axis and two long-axis views) were acquired in each subject using the following sequence parameters: bSSFP, TR1.09/TE0.9ms, image matrix 160×80, flip angle 58°, resolution 2.44×2.44 mm^2, 1420Hz/pixel, acceleration rate R=4 with time-interleaved sampling of k-space. ***Perfusion imaging:*** 10 healthy volunteers (6 males; age 21.7−41.2yrs) underwent free-breathing real-time exercise stress EPI perfusion examinations with written consent. The same scanning facilities were used as the cine imaging. Three short-axis slices were acquired in each subject using the following sequence parameters: GRE-EPI readout, TR5.6/TE1.1ms, image matrix 160×108, flip angle 25°, resolution 1.72×1.72 mm^2, 434Hz/pixel, R=2 with time-interleaved sampling of k-space. ***TSPIRIT:*** As shown in Figure 1, all temporally interleaved k-space frames were averaged to generate auto-calibration (ACS) signals and GRAPPA was first used to estimate full k-space for every frame. Karhunen-Loeve transform filtering was applied on outcome of GRAPPA and to improve SPIRIT kernel estimation and suppress artifacts. For every frame, its SPIRIT calibration was computed on the filtered full kspace data. The under-sampled k-space and estimated kernels served as inputs to non-linear solvers. The LSQR matrix inversion solver was firstly performed to solver the linear SPIRIT equation, and then a non-linear conjugate gradient solver was called with spatial wavelet and total variation regularization. Final images were generated after convergence and compared to images of conventional TGRAPPA reconstruction [3] of the same raw data. The phased array combination coefficients were estimated using the Rank-1 eigen-analysis [4]. The final SNR optimal images were computed by performing a B1-weighed array combination with the noise correlation matrix estimated from the separate noise-only readouts. ***SNR quantification:*** To quantify the increase of signal-noise ratio, a fully automated retrospective noise variance estimation algorithm [5] based on the random matrix theory and Marcenko-Pastur distribution was applied. With the solid mathematical basis, this method proves to be accurate for dynamic imaging series. ***Ghosting artifact quantification:*** The severity of ghosting artifacts caused by parallel imaging techniques and/or the chest wall motion were quantified by the peak of spatial autocorrelation of reconstructed image along the phase-encoding direction [6], because the time-interleaved sampling pattern leads to regular aliasing appearing at the positions corresponding to fractions of the FOV that match the acceleration rate.

Results All results were visually inspected to ensure the success of proposed reconstruction. As demonstrated in Figures 2 and 3, the improved SNR is noticeable while the artifacts do not rise for the TSPIRIT approach. Compared to the TGRAPPA reconstruction, the proposed method leads to significant SNR gain. Compared to SPIRIT reconstruction with averaged-all ACS signal estimation, the proposed method leads to lower ghosting artifacts (Figure 2). Table 1 summarized the quantitative measures of relative SNR (the SNR of TGRAPPA was normalized to be 1 and relative ratio of SNR gain was computed for every dataset) and artifact ratio. Compared to TGRAPPA, the relative SNR gain is 28.5% for cine and 19.7% for perfusion. The quantified artifacts are statistically unchanged while the SNR increase is significant.

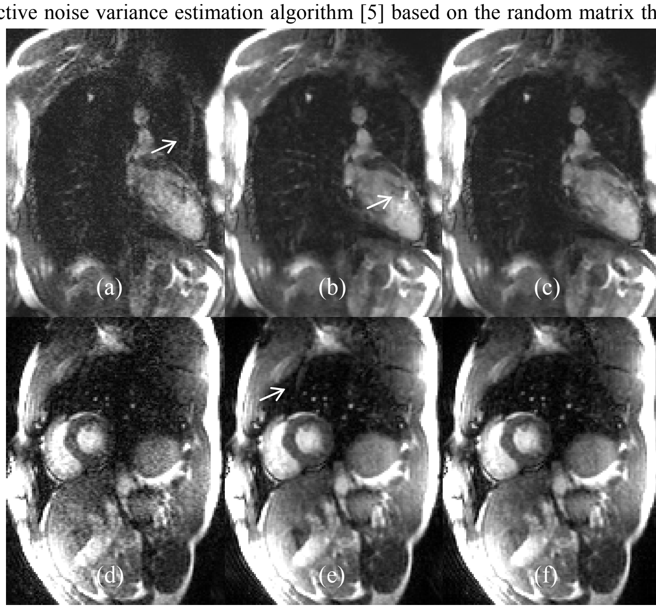

Figure 2. Example cine images acquired using R=4 and reconstructed using linear TGRAPPA (a,d) and SPIRIT with averaged-all ACS signal estimation (b,e) and non-linear TSPIRIT (c,f). Note increase in SNR with TSPIRIT and reduced artifact. With the proposed ACS signal estimation and calibration scheme, ghosting artifacts do not increase.

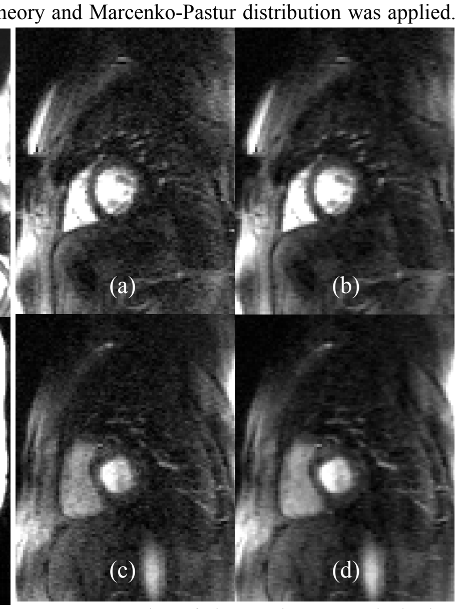

Figure 3. Example perfusion EPI images acquired using acceleration rate 2 and reconstructed using linear TGRAPPA (a,c) and non-linear TSPIRIT (b,d). The SNR gain of proposed TSPIRIT reconstruction is noticeable compared to the TGRAPPA reconstruction.

Table 1. The quantitative measures of reconstruction quality.

	Cine						*Perfusion*			
	SNR			*Artifacts*			*SNR*		*Artifacts*	
	TGRAPPA	*SPIRIT*	*TSPIRIT*	*TGRAPPA*	*SPIRIT*	*TSPIRIT*	*TGRAPPA*	*TSPIRIT*	*TGRAPPA*	*TSPIRIT*
Mean	1	1.307	1.285	0.131	0.133	0.130	1	1.197	0.166	0.166
STD	-	0.172	0.140	0.038	0.038	0.038	-	0.084	0.063	0.063
P-value	***TGRAPPA*** vs. ***SPIRIT*** : <1e-5 ***TGRAPPA*** vs. ***TSPIRIT*** : <1e-5 ***SPIRIT*** vs. ***TSPIRIT*** : 0.241			***TGRAPPA*** vs. ***SPIRIT*** : <1e-5 ***TGRAPPA*** vs. ***TSPIRIT*** : <1e-5 ***SPIRIT*** vs. ***TSPIRIT*** : <1e-5			<1e-5		0.722 no significant difference	

References [1] Jekic M, et al., JMRI 10:3 (2008) [2] Lustig M, et al., MRM 64:457-471 (2010) [3] Breuer FA, et al., MRM 53(4):981-985 (2005) [5] Ding Y, et al., MRM 63(3):782-789 (2010) [6] Ding Y, et al., MRM 65(6):1786-1792 (2011)