# Highly accelerated myocardial perfusion MRI using k-t SLR with parallel imaging

**S. Lingala[1], Y. Hu[2], E. Dibella[3], and M. Jacob[1]**
[1]Biomedical Engineering, University of Rochester, Rochester, NY, United States, [2]Electrical and Computer Engineering, University of Rochester, Rochester, NY, United States, [3]Radiology, University of Utah, Salt Lake city, UT, United States

**INTRODUCTION:** In quantitative myocardial perfusion MRI, it is desirable to have high spatio-temporal resolution, good volume coverage and high SNR image acquisitions. This is often challenging due to the restricted diastolic image acquisition window. Schemes such as k-t BLAST/k-t SENSE have been proposed to address these requirements [1]; they have shown to operate upto 5 fold acceleration *(R)* in breath held studies. However, at this *R*, compromises between these image parameters still exist. For instance, in [2], with $R = 5$, improved spatial resolution ($1x1mm^2$) was achieved at the expense of reduced volume coverage (3 slices). Principal component analysis (PCA) based schemes have been proposed to overcome the limitations associated with k-t BLAST/k-t SENSE to operate at high *Rs* [3,4]. The practical realization of these schemes rely on a dual k-t sampling pattern and a two step reconstruction algorithm of first estimating the temporal bases and next the dynamic images. This strategy has shown to have trade-offs between accurate temporal modeling and spatial artifact suppression [5]. We proposed an efficient dynamic framework that's radically different from these PCA based schemes; our approach overcomes the trade-off by directly recovering the temporal bases and spatial weights from the measured data [5]. In this paper, we extend our framework (k-t SLR: based on Low Rank and Sparsity penalties) to include additional information from multiple coils in parallel imaging and demonstrate its utility in acquiring perfusion images at high *Rs (>10)*.

**THEORY:** The singular value decomposition (SVD) of the dynamic signal matrix $\mathbf{\Gamma}$ reveals few significant singular values explaining the low rank nature of the dynamic signal i.e, the signal can be modeled as a linear combination of few (*r*) temporal bases ($v_i(t)$) (eq.1). We pose the recovery of $\mathbf{\Gamma}$ as a spectrally regularized problem in (eq.2). Here, **b** contains the acquired k-t samples and *A* accounts for the Fourier and coil sensitivity encoding. We exploit (i) the low rank property by using the non-convex Schatten spectral p-norm, defined as in (eq.3); this has the capability of penalizing small singular values, which are often associated with artifacts, (ii) the sparse gradients of dynamic images by the total variation (TV) norm. We solve our optimization criteria by using a fast augmented Lagrangian (AL) method [6]. We employ the AL method to significantly reduce the computational time in reconstructing $\mathbf{\Gamma}$. Specifically as shown in fig.1, we obtain a speed up of 4-5 fold, when compared to our earlier implementation in [5]. Our algorithm takes a total processing time of 1-2 mins for single channel and 4-5 mins for multi channel reconstructions on a NVDIA Tesla graphical processing unit.

$$\Gamma = \mathbf{U}_{n_x n_y \times n_t} \Sigma_{r \times r} \mathbf{V}^*_{r \times n_t}; \quad \gamma(\mathbf{x},t) = \sum_{i=0}^{r-1} \sigma_i u_i(\mathbf{x}) v_i(t) \quad (1)$$

$$\min_{\Gamma} \|A(\Gamma) - \mathbf{b}\|^2 + \lambda_1 \left( \|\Gamma\|_p \right)^p + \lambda_2 \left\| \sqrt{|\nabla_x \Gamma|^2 + |\nabla_y \Gamma|^2 + |\nabla_t \Gamma|^2} \right\|_{l_1} \quad (2)$$

$$\left( \|\Gamma\|_p \right)^p = \sum_{i=0}^{n_t} \sigma_i^p \quad (3)$$

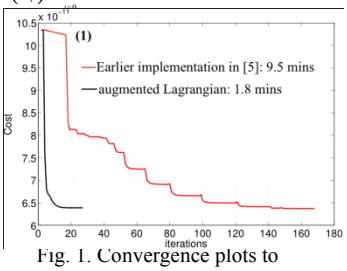
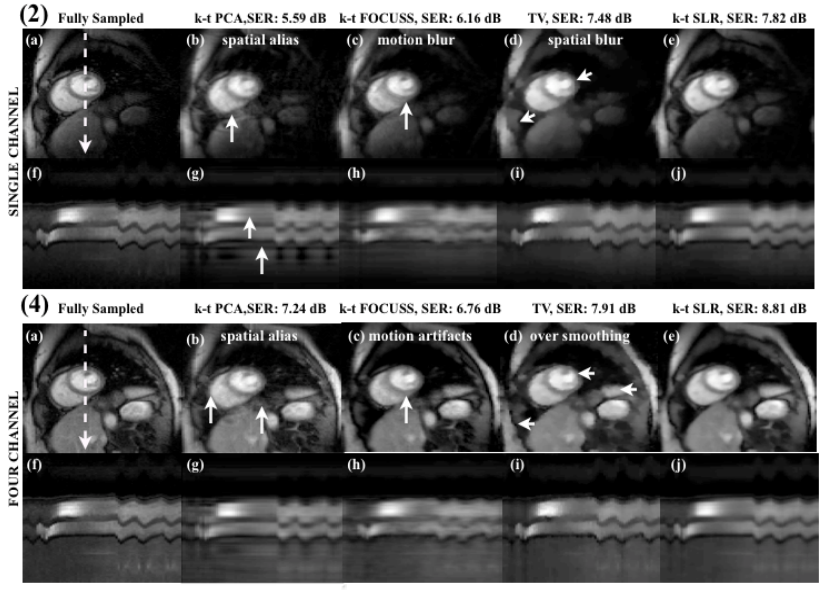
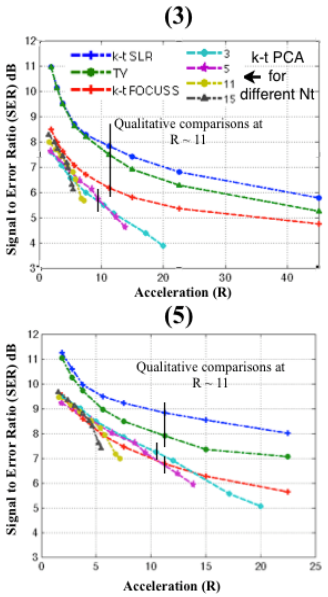



Fig. 1. Convergence plots to demonstrate the performance speed up obtained by the AL method

**METHODS AND MATERIALS:** To demonstrate the performance of k-t SLR-parallel MRI, we retrospectively down sample fully sampled cardiac perfusion data (phase x frequency encodes x time frames x coils: 90x190x70x4) acquired with a FLASH saturation recovery sequence on a Siemens 3T scanner at the University of Utah. We compare our k-t SLR method against (1) the conventional two step k-t PCA scheme [4] with different dual k-t sampling patterns at a range of training sizes (Nt), (2) k-t FOCUSS [7] which is a x-f space based method, (3) a regularized scheme that relies on a spatio-temporal TV penalty [8]. We perform both multi channel and single channel comparisons. Assuming time invariance of coil sensitivities, we estimate them by using sum of squares from the temporally averaged images. k-t PCA uses Cartesian trajectories. All the other schemes use an equi-angled radial trajectory in each frame, which is rotated by a random angle across frames to achieve incoherent sampling. Finally, we use a signal to error (SER) ratio metric defined as $-10\log_{10}\left(\|\Gamma_{fs} - \Gamma_{rec}\|_F^2 / \|\Gamma_{fs}\|_F^2\right)$ to quantify the difference between the reconstructed and fully sampled data sets.

**RESULTS AND DISCUSSIONS:** Figures (2,3) and (4,5) respectively show the single and four channel comparisons. As is seen in the SER plots (figs 3,5), k-t SLR outperforms the rest of the schemes consistently at most accelerations *(R)*. Specific visual comparisons at R~11 in figs (2,4) show that k-t SLR is robust to the many inaccuracies of the other schemes. Specifically, k-t PCA shows a trade –off in spatial artifact suppression for temporal accuracy; (here we picked the best k-t PCA scheme based on the SER, see figs 3, 5). k-t FOCUSS has temporal blurring across frames due to motion artifacts (arrows in figs2(c), 4(c)). TV based schemes show blurring of important details such as the edges of the myocardial cavities (arrows in figs 2(d), 4(d)). With the multi channel acquisitions, the signal qualities and SERs of all the schemes were increased. However, we observe in fig. 3 that k-t PCA, k-t FOCUSS, TV based schemes still suffer from the inherent inaccuracies characteristic of their schemes. In contrast, k-t SLR with parallel MRI provides superior reconstructions (by a factor of at least 1dB) with minimal blur. We argue that the speed up with k-t SLR could be utilized to significantly reduce the trade offs in spatio-temporal resolution, volume coverage and SNR routinely seen in myocardial perfusion MRI for an accurate quantitative study.




Performance evaluation of different methods using single channel (figs.2,3) and multi channel (figs 4,5) comparisons. A spatial frame and the image time series through the arrow pointed in 2(a) and 4(a) are shown for the fully sampled, k-t PCA, k-t FOCUSS, TV based and the k-t SLR methods. The SER v/s acceleration plots are shown in (figs.3,5). It is seen both from the quantitative and qualitative comparisons that k-t SLR provides efficient reconstructions while being robust to many artifacts and inconsistencies, that are observed in the remaining methods.

**REFERENCES:**

[1] Tsao.J et.al, MRM 2003
[2] R. Manka et.al, JACC Cardiovascular 2010
[3] C. Brinegar et.al,EMBC 2008
[4] H. Pedersen et.al, MRM 2009
[5] S. Goud et.al, ISBI 2010
[6] M. Alfonso et.al, IEEE-TIP 2010
[7]H.Jung et.al, MRM 2009
[8]G.Adluru et.al, JMRI 2009