High resolution structural free-breathing cardiac MRI using k-t SLR

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INTRODUCTION:

High-resolution structural imaging of the heart has several applications including delayed enhancement imaging [1] and fat-water separation to detect fibro-fatty infiltration [2]. The standard acquisition scheme requires the subjects to hold their breaths during the imaging to eliminate respiratory motion induced artifacts; the data is acquired during the diastolic phase of each heart beat. The multiple breath-holds that are required to acquire multi-slice data is often challenging for many subjects. Free-breathing structural cardiac MRI using ultra fast sequences with respiratory navigator pulses has been proposed to overcome this problem [3]. The main challenge with these schemes is the imperfect correlation between cardiac and diaphragm dynamics, sensitivity to breathing pattern changes, and the low acquisition efficiency. We recently proposed a novel scheme termed as k-t SLR to significantly accelerate dynamic cardiac MRI [4]. This scheme exploits the similarity between the intensity profiles of voxels by modeling the dataset as a low-rank matrix; this implies that the voxel profiles can be expressed as a weighted linear combination of a few principal temporal basis functions $v_i(t)$:

$$\gamma(\mathbf{x},t)=\sum_{i=0}^{r-1}\rho_i(\mathbf{x})v_i(t)$$

where $\gamma(\mathbf{x},t)$ is the matrix of the spatio-temporal signal, r is the rank of the matrix and $\rho_i(\mathbf{x})$ are the spatial weights of the temporal basis functions. Fig 1 is an illustration of this scheme. This formulation significantly reduces the number of degrees of freedom. For example, if $v_i(t)$ are known apriori, the reconstruction simplifies to the recovery of r images $\rho_i(\mathbf{x})$ [5]; this is often much smaller than the number of time frames in the dataset. To overcome the problems associated with respiratory-gated cardiac imaging, we propose to reformulate the structural imaging problem as the recovery of a 2D+time dataset from undersampled data. We propose to collect part of the k-space data during the diastolic phase of each heartbeat and recover the 2D+time dataset using the k-t SLR scheme. The temporal basis functions $v_i(t)$ enable the data sharing between multiple heartbeats, thus facilitating the recovery of the unknown images $\rho_i(\mathbf{x})$. Once the high resolution dataset is recovered, the structural image at any respiratory phase can be obtained. The images could also be registered and averaged to improve the SNR.

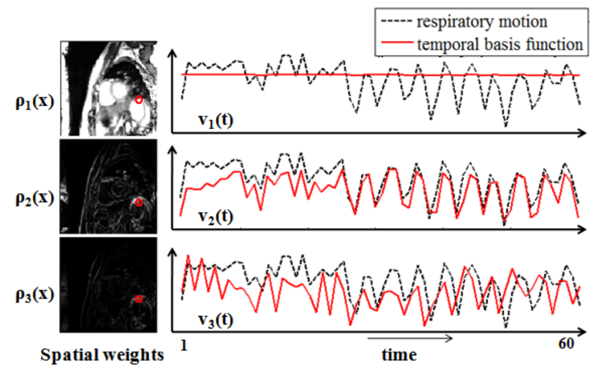

Fig 1: Schematic of k-t SLR based reconstruction. PCA gives the temporal basis functions and the corresponding spatial weights, which enables the data sharing between heartbeats. The respiratory motion is tracked according to the motion of the pixel in red spot.

METHODS:

We pose the reconstruction as a matrix recovery problem of recovering a sparse and low rank matrix $\mathbf{X}$ from its undersampled measured k-space data, specified by $\mathbf{b}=\mathrm{A}(\mathbf{X})+\mathbf{n}$, where A is the Fourier undersampling operator. We solve the problem using a regularized optimization reconstruction scheme with two penalties: 1. Non-convex Schatten p-norm matrix penalty to improve the recovery rate; 2. sparsity penalty as the sum of the TV norm of the images since dynamic MR images have sparse gradient:

$$\mathbf{X}^*=\arg\min_{\mathbf{x}}\|\mathrm{A}(\mathbf{X})-b\|^2+\lambda_1\|\mathbf{X}\|_p^p+\lambda_2\mathrm{TV}(\mathbf{X})$$

Here $\|\mathbf{X}\|_p^p=\sum_{i=1}^{\min\{m,n\}}\sigma_i^p$ and $\mathbf{X}=\mathbf{U\Sigma V}^*$ is the singular value decomposition (SVD) of the signal where $\mathbf{\Sigma}=\mathrm{diag}([\sigma_0,\sigma_1,..\sigma_{r-1}])$.

To determine the utility of this scheme, we acquired fully sampled free breathing cardiac MR data with a matrix of 128×128 from 60 heartbeats. This data was retrospectively downsampled using a radial undersampling scheme. We vary the number of radial lines/heartbeat and aim to recover the images using the proposed scheme. We also compare our method with TV reconstruction.

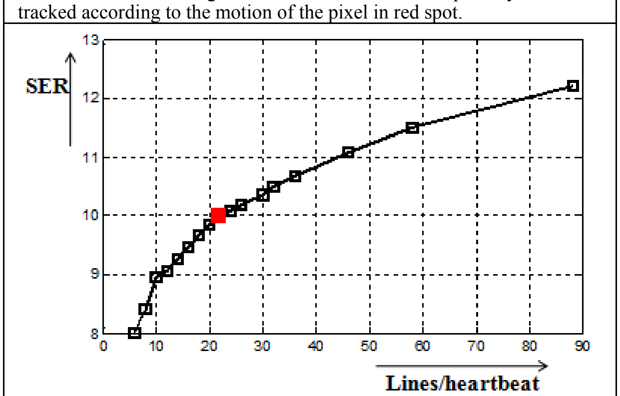

Fig 2: function of SER (y direction) to the number of radial lines in k-space (x direction). The red square at 22 lines points to the specific comparisons shown in Fig 3. We could get reconstructed images with high spatial resolution by more than 20 lines, where the acceleration is 7.

RESULTS AND DISCUSSION:

We quantify the performance of the algorithm using the signal to error ratio (SER) computed as the logarithm of the root mean square error (RMSE) between the reconstructions and the original data we used. Results of the reconstructions are shown in Fig 2 by the function of SER to the number of radial lines collected in each time frame. One specific reconstruction comparison between the proposed scheme and TV reconstruction is shown in Fig 3. We observe that the combined scheme improves the reconstruction significantly over the reconstruction with only the TV penalty. Note that we obtain good reconstructions with only 20 radial lines and single channel free breathing cardiac MR data; we expect to further decrease the number of lines by incorporating parallel imaging techniques and 3D acquisition. Thus, this approach can enable the acquisition of free breathing multi-slice late gadolinium enhancement (LGE) MRI data, without navigators.

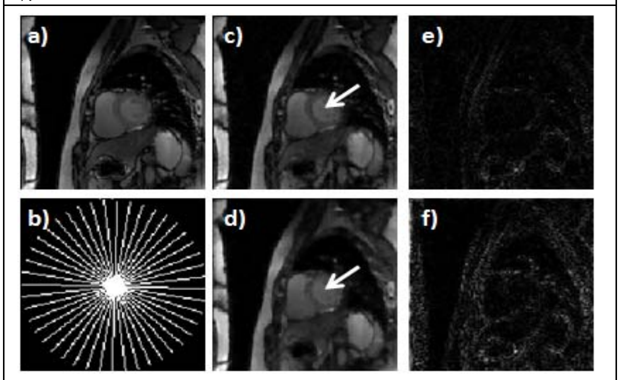

Fig 3: Reconstruction results with 22 lines: a) first time frame of the original free breathing cardiac MR images; b) radial undersampling trajectory; c) reconstruction with proposed scheme with SER 9.98 and the error is plotted in e); d) TV reconstruction with SER of 8.87 and the error is plotted in f). Noted that the TV scheme blurred the image.

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