Non-segmented Free-breathing Cardiac Imaging using Low-rank Matrix Completion with a k-space Variant Constraint

Yu Y. Li[1]
[1]*Radiology, Imaging Research Center, Cincinnati Children's Hospital Medical Center, Cincinnati, Ohio, United States*

Target Audience: Researchers in the field of image reconstruction and cardiac imaging.

Purpose: It is desirable to collect free-breathing cardiac MRI data without k-space segmentation. The clinical benefits include the ability to examine non-periodic cardiac behaviors (e.g. arrhythmias) and scan patients who cannot hold their breath (e.g. neonates). Non-segmented free-breathing cardiac imaging requires dynamic data to be collected faster than respiratory and cardiac motion in every time frame. High undersampling is typically needed. The presented work investigates a low-rank matrix completion approach [1, 2] to k-t space image reconstruction from highly undersampled data. It is found that the low-rank nature of k-t space data matrix is dependent on k-space locations due to motion sensitivity differences and k-t imaging can benefit from region-by-region image reconstruction. This work demonstrates that low-rank matrix completion can generate high-quality multi-cycle multi-phase cardiac images from non-segmented data collected at a speed of <50 ms per time frame with free-breathing.

Methods: It has been demonstrated that low-rank matrix completion can recover missing data without calibration in parallel imaging [1, 2]. The underlying mechanism is that multi-channel k-space data can be organized into a structured matrix (e.g. Hankel-like matrix) that has a low rank due to k-space data correlation. By jointly imposing low-rank and data-fidelity constraints to the data matrix, missing data can be reconstructed iteratively. In non-segmented free-breathing cardiac imaging, k-t space data are sparse along the time direction because motion information is concentrated within the respiratory and cardiac frequency bands, which are typically narrow. This sparsity can introduce data correlation between every two time frames that may be in the same or different cardiac cycles. It is found in the presented work that data correlation along time dominates that in k-space and motion primarily determines the rank of a data matrix formed from multi-channel k-t space data. Furthermore, because motion sensitivity of MRI data increases with their distance to the k-space origin, the data matrix formed from multi-channel k-t space data has a low-rank nature with k-space variation. For this reason, the presented work introduces a k-space variant constraint in low-rank matrix completion and the missing k-t space data are reconstructed in a region-by-region fashion. This region-by-region image reconstruction can be formulated as follows:

$$\hat{y} = \arg\min_{\hat{y}} \sum_{k} \left\| P\{D_k(\hat{y})\} - y \right\|^2 \text{ subject to } rank[D_k(\hat{y})] = r(k) \qquad (1),$$

where $\hat{y}$ represents reconstructed data, P is sampling projection, y represents collected data, D_k is the data matrix formed from multi-channel k-t space data located in a k-space region indexed by k and $r(k)$ is the k-space variant low-rank constraint on D_k. The image reconstruction described by Eq. 1 has several differences from SAKE [1] or LORAKS [2]. First, k-t space data are organized into multiple data matrices (D_k, k is a k-space region index) with each formed from data located in a local k-space region (Figure 1). Second, the data matrices D_k's are not structured. Third, the low-rank constraint $r(k)$ is k-space variant and reflects motion sensitivity variation in k-space. Empirically, we use a constraint proportional to the distance of k-t space data D_k to the k-space origin, i.e., $r(k) \propto |k|$.

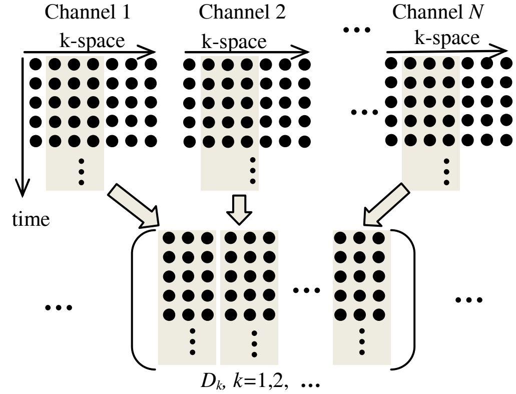

Figure 1. Formation of data matrices from k-t space data.

To validate the approach, a cardiac imaging experiment was conducted using a 32-channel coil array and a 3T clinical MRI scanner. Segmented CINE data were first collected for references using a 2D ECG-gated multi-shot bSSFP sequence (FOV 320×320 mm, matrix 160×160, TR/TE 2.3/1.2 ms, TFE factor=20, flip angle 30°, scan time 8 s, 30 cardiac phases). Non-segmented free-breathing cardiac CINE data were then collected using a 2D single-shot bSSFP sequence (FOV 320×320 mm, matrix 160×160, TR/TE 2.1/1.1 ms, flip angle 25°, scan time 5 s) without ECG monitoring. The data acquisition speed was ~37 ms per time frame. Each time frame included 16 phase encoding lines. The presented approach was used to reconstruct non-segmented free-breathing data. An online k-t SENSE [3] method was used as a reference approach.

Results: Figure 2(a) shows the first 200 singular values of k-t data matrices (D_k's in Figure 1) calculated from fully sampled segmented CINE data in different k-space regions. It can be seen that the matrix rank increases with the distance of data to the k-space origin. Figures 2(b) and 2(c) show the reconstruction results. It can be seen that both segmented imaging and low-rank matrix completion can generate excellent image contrast and temporal resolution while k-t SENSE cannot. In comparison to segmented imaging, low-rank matrix completion gives more information with less acquisition time: Segmented imaging gives single-cycle images in 8 s while low-rank matrix completion gives multi-cycle images in 5 s.

Discussion: Because respiration and heart beat are pseudo-periodic, cardiac data collected in different times have correlation. Conventional k-t space techniques [3, 4] can use data correlation only between neighboring time frames. By organizing k-t data into data matrices as in Figure 1, low-rank matrix completion can utilize data correlation across all different cardiac phases or cycles. Due to the use of more data and information than conventional k-t space techniques, a gain in image reconstruction can be achieved. It should be noted that temporal data correlation may be reduced by motion. For this reason, a data matrix from outer k-space has a higher rank because its data are more sensitive to motion (Figure 2a).

Conclusion: Low-rank matrix completion can generate high-quality cardiac images from data collected at a speed of <50 ms per time frame. With multi-cycle multi-phase images, non-periodic cardiac behaviors can be investigated, which is not feasible using segmented data acquisition.

References: 1. Shin, P et al., MRM 2014, 72: 959-970. 2. Haldar, JP, IEEE Trans Med Imaging 2014, 33: 668-681. 3. Tsao, J et al., MRM 2003, 50: 1031-1032. 4. Huang, F et al., MRM 2005, 54: 1172-1184.

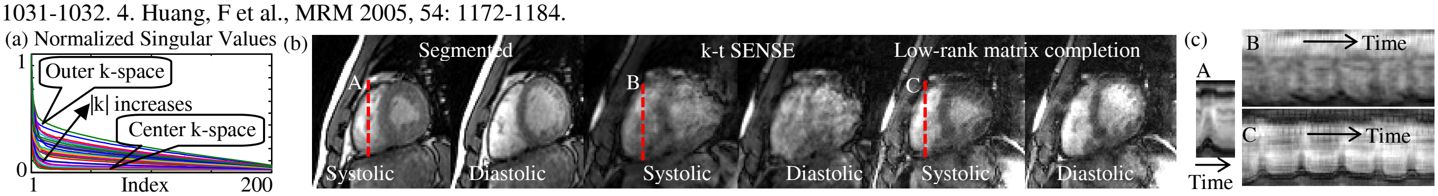

Figure 2. (a) Plots of singular values (normalized to the first singular value in each plot) of the data matrices formed from fully sampled segmented data located in different k-space regions. (b) Reconstructed images. (c) Reconstructed time trajectories along the red lines in (b). Non-segmented data (B and C) give multi-phase images in ~5 sequential cardiac cycles while segmented data (A) give images only in a single cardiac cycle. Non-periodic behaviors can be seen.