Reconstruction for Dynamic 2D-Radial Cardiac MRI Using Prior Enhanced Compressed Sensing

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Introduction: Radially encoded MR imaging (MRI) has been well adopted in the field of fast imaging, due to its robustness to motion and relatively high signal to noise ratio (SNR) compared to the direct Fourier imaging. In many of its applications, however, the trajectory is under-sampled to reduce scan time and capture fast physiological changes. Conventional gridding reconstruction from under-sampled data introduces severe streaking artifacts and results in low SNR. Recently, compressed sensing (CS) theory emerges as a promising approach that can accurately reconstruct a signal f even when its indirect measurement is severely undersampled. In practice, measurement imperfections and noise are present, so the data reduction factor promised by CS is clearly reduced. In the sense of a Bayesian formulation, the sparsity is the only prior knowledge exploited in the basic CS approach. Effort, for instance [1,2], has been devoted to incorporating more prior estimates in the CS framework. In this work, it is shown that the reconstruction results for dynamic 2d radial cardiac MRI can be improved by additional prior obtained from combining the interleaved samples in the dynamic image sequence.

Methods: A conventional unconstrained formulation of CS can be expressed as

$$\arg\min_f \{\| Af - y \|_2^2 + \lambda \| \varphi(f) \|_1\}. \quad (1)$$

Here, f is a trial image; φ is a sparsifying transformation; y is the measured k-space data; A is an encoding matrix that includes coil sensitivity profiles and the Fourier operator; and λ is a Lagrange multiplier that weights between the data fidelity and the L1 regularization terms. Eq. (1) is the conventional CS formulation that solely relies on the sparsity assumption. For the particular application of the radial acquisition, streaking is the most evident aliasing artifacts. In this case, the reconstruction challenge can be relieved if prior knowledge about the artifact locations is known. Fortunately, in dynamic 2D radial cardiac MRI with spoke interleaves that are rotated from one frame to another, it is possible to reconstruct a nearly artifact-free high-resolution image g from all non-overlapping samples, at the expense of sacrificing the temporal resolution. Inspired by k-t SENSE [3] that requires a signal variance estimate in the regularization term, we here try to reconstruct time-resolved images with the help of the prior image g, whose lowpass version g_L will serve as a smoothly varying weighting function, as in k-t SENSE. When g_L is temporally concatenated to match the size of f, and then denoted by g_P, Eq. (1) can be modified to take into account the additional weighting as

$$\arg\min_f \{\| Af - y \|_2^2 + \lambda \| \varphi(g_P \bullet f) \|_1\}, \quad (2)$$

where ● denotes an element-wise multiplication. This revised formulation is referred to as PRIior eNhanCEd CS (PRINCE-CS). It is observed that choosing the composite of the redundant Haar wavelet transform in the spatial domain and the Karhunen-Loeve transform (KLT) in the temporal dimension yields a good balance between detail preservation and artifact/noise suppression. The introduction of g_P in the forward imaging model reduces the streaking strength in the L1 regularization term $f_P = g_P \bullet f$, making it sparser. While solving Eq. (2) generally involves the shrinkage operation, the reduction in both the artifact and the noise amplitudes in f_P enables the solver to shrink them toward 0, thus eliminating most of the artifacts and improving SNR.

Results: Example measurement data was obtained from a pig with a high heart rate at 120 bpm, using a Siemens MAGNETOM Espree 1.5T with a TrueFISP sequence. There are 4 non-overlapping interleaves in the k-space trajectory, which are combined to construct the prior image g_P via the standard gridding algorithm. Each interleave/phase contains 8 projections, each with 256 samples (2x oversampled for the target matrix size 128x128). The numbers of channels and phases are, respectively, 18 and 24. Because the encoding matrix A accounts for coil sensitivity, SENSE based paralleling imaging is included and the coil sensitivity profiles were estimated from non-overlapping samples according to [4]. NUFFT [5] is used to transform between k-space and the image domain; and the FISTA algorithm [6] was adopted to solve Eqs. (1) and (2) with 30 iterations and $\lambda = \|A^* y\|_\infty$, where A^* denotes the adjoint of A. Fig. 1(a) shows the reconstruction of the first frame using gridding, which indicates the severity of the aliasing artifacts. The x-t plots for the results from k-t SENSE and the proposed method are shown, respectively, in Figs. 1(h) and 1(i). Please refer to the figure caption for details.

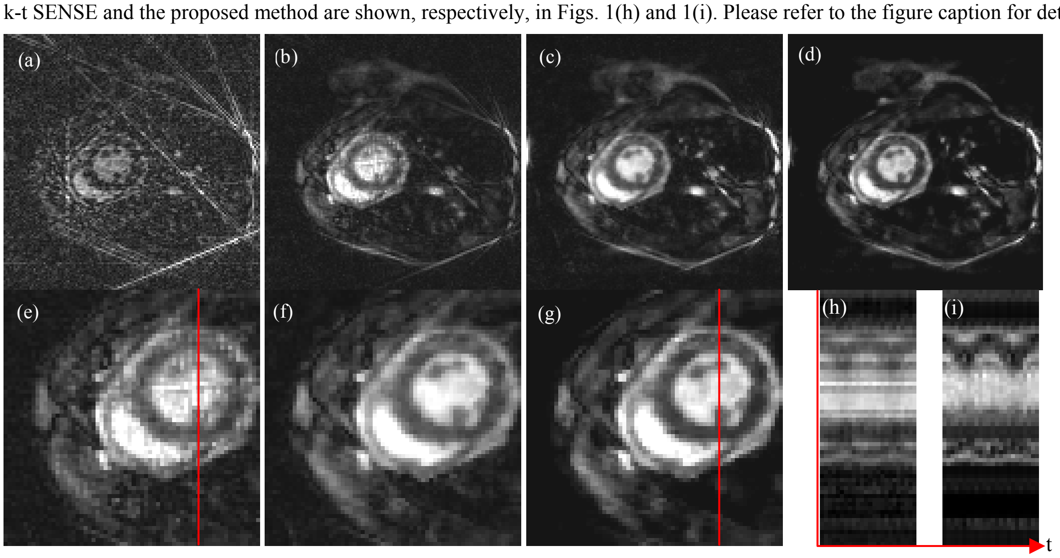

Fig. 1 First frame of the dynamic image sequence reconstructed by (a) gridding, (b) k-t SENSE, (c) CS using Eq.(1), and (d) PRINCE-CS using Eq.(2). To better illustrate the difference, (b), (c), and (d) are cropped, magnified, and shown, respectively, in (e), (f), and (g). At 8 projections per frame, the result (e) from k-t SENSE shows strong artifacts and low SNR. The CS result (f), using spatial redundant Haar wavelet transform and temporal KLT, eliminates much of the artifacts. With additional prior, result (g) obtained from PRINCE-CS demonstrates improved SNR compared to (f). The x-t plots at the red vertical profiles for (e) and (g) are shown, respectively, in (h) and (i). The temporal resolution (i) is reasonably good compared to (h).

Discussion and Conclusion: For the reconstruction of dynamic 2d radial cardiac MRI, the concept of prior-enhanced CS was realized by introducing a nearly artifact-free estimate into the L1 constraint term. By utilizing the composite transform of the spatial redundant wavelet transform and the KLT in the temporal dimension, good reconstruction quality with visually low aliasing artifacts and high SNR can be consistently achieved for other 6 similar data sets at hand. Another observation is that due to interleaved radial trajectories for different phases, both the streaking artifacts and the heart are moving. Care must be taken in determining a suitable regularization weight to balance between motion preservation and artifact supression. The challenge of distinguishing different dynamic patterns, either caused by actual motion or rotating streaking artifacts, is a direction for future research.

References

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