Robust Single-Shot Hyperpolarized ^{13}C Spectroscopic Imaging Utilizing Incoherent k-t spiral Sampling and Low-Rank Matrix Completion

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Audience: Researchers interested in robust and quantitative dynamic imaging with hyperpolarized ^{13}C substrates.

Purpose: Successful clinical translation of hyperpolarized ^{13}C imaging requires the availability of robust and efficient time-resolved spectroscopic imaging strategies. Recent advances have enabled increased temporal resolution[1-3] yet imaging remains highly challenging in regions with respiratory and cardiac induced motion and may be insufficient for accurate quantitative modeling. In this work, we investigate the synergistic combination of both intra and inter-spiral correlations for improved spectroscopic imaging with k-t spiral[4].

Theory: In the k-t spiral sampling technique[4], k-space is oversampled η times greater than required by the Nyquist criterion, resulting in η effective echo times per shot that can be used for spectral separation**.** Due to gradient limitations, it is often impossible to achieve optimal temporal spacing of these pseudo-echo times, resulting in reconstruction instabilities and poor noise performance. To reduce gradient requirements and stabilize the reconstruction we propose to use both the intra- and inter-spiral correlations as shown in **Fig. 1**. For a dynamic dataset, k-t space is sampled with oversampled single-shot k-t spirals; however, unlike previous designs each timeframe is sampled with a permuted k-t spiral trajectory. This enables the use of robust low-rank approximation[5] to reconstruct images posed as the minimization of $||E(\psi)x-d||_2+\lambda||R_t x|$, where λ is a regularization factor, R_t reformats images as a pixel vs time matrix (**Fig.1**) and $||\ |$ is the nuclear norm (sum of singular values).

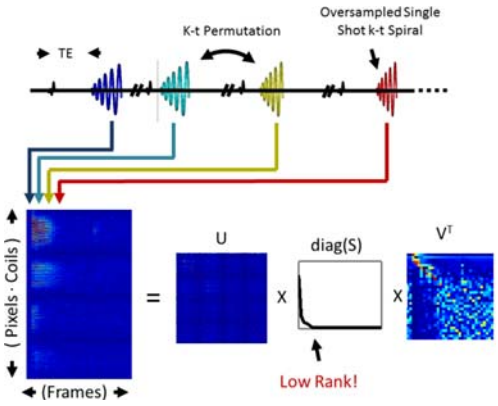


Figure 1*. Permuted k-t sampling and low-rank representation in the singular value domain.*

Methods: Digital simulations were performed with data generated assuming [1-^{13}C]pyruvate in exchange with alanine, lactate, and pyruvate-hydrate at 4.7T. Data were generated with a single echo, $\eta = 4$ spatially oversampled spiral trajectory in two fashions; one using a constant TE and a second for which the TE was chosen pseudo-randomly for each timeframe (k-t permutation). Complex Gaussian noise was added and data were reconstructed with iterative thresholding with and without low-rank penalty. At each noise level, root mean square error (RMSE) was calculated for the reconstructed images compared to a conventional 5-echo acquisition. To demonstrate in-vivo feasibility, images of [1-^{13}C]pyruvate murine renal metabolism were acquired at 4.7T with the same k-t trajectory and reconstructed with and without k-t permutation.

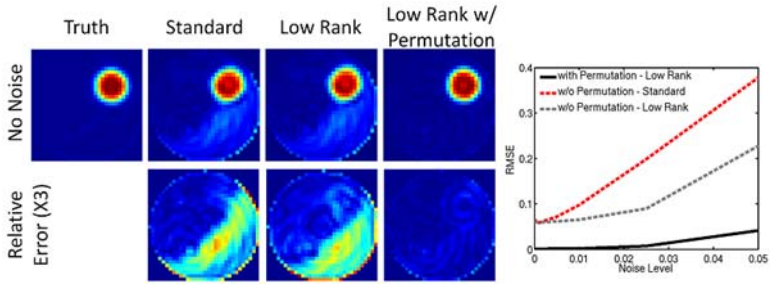
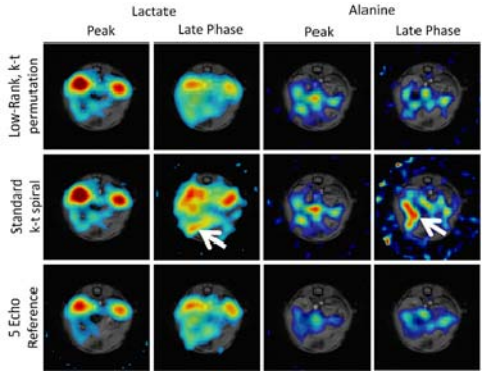


Figure 2. *Representative metabolite images from digital simulations demonstrate improved RMSE for permuted k-t sampling and low-rank regularization.*

Figure 3. *Permuted k-t sampling and low-rank regularization leads to a reduction in reconstruction error in-vivo compared to standard k-t spiral (arrows).*



Results & Discussion: Even in the absence of noise, k-t reconstructions without TE permutation show substantial error (**Fig. 2**), arising from suboptimal intra-spiral temporal spacing at the center and edge of k-space. While low-rank regularization has a denoising effect, it does nothing to improve the conditioning of the encoding matrix and hence does not resolve the error in the noiseless case. An introduction of a permutation between TEs yields a well-conditioned inverse by exploiting temporal correlations across adjacent images in time. A similar trend is seen for in-vivo images (**Fig. 3**). Substantial improvements are observed when data is reconstructed with k-t permutation and low-rank regularization for late phase images of product metabolites with low signal. This is reflected in the RMSE which drops from 0.33 to 0.26 in pyruvate, 0.38 to 0.26 in lactate, 0.90 to 0.49 in pyruvate-hydrate, and 1.15 to 0.51 in alanine using permuted k-t sampling in conjunction with low-rank regularization.

Conclusion: Joint reconstruction and k-t spirals are powerful tools for highly accelerated ^{13}C imaging of metabolism that show potential to complement parallel imaging acceleration for dynamic imaging of hyperpolarized metabolites. Ongoing work will refine and verify accuracy for quantitative kinetic analysis of substrate and product metabolites from these highly accelerated reconstruction strategies.

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References: [1] Morze et al. 2011 JMRI 211(2):109. [2] Meyer et al. 2010 JMRI 204(2):340. [3] Wiesinger et al. 2011 MRM 68(1):8. [4] Gordon et al. 2013 MRM doi.10.1002/mrm.24796 .[5] Candes et al. 2011 ACM 58(3):1.