

Joint K-T Reconstruction and Oversampled Spirals for Single-Shot 2D Spatial/1D Spectral Imaging of ^{13}C Dynamics

Jeremy W Gordon¹, David J Niles¹, Sean B Fain^{1,2}, and Kevin M Johnson¹

¹Medical Physics, University of Wisconsin-Madison, Madison, WI, United States, ²Radiology, University of Wisconsin-Madison, Madison, Wisconsin, United States

INTRODUCTION: Hyperpolarized (HP) ^{13}C experiments require rapid, efficient spatial and spectral imaging to resolve all chemical species. While rapid spectroscopic imaging techniques exist, such as echo planar spectroscopic imaging (EPSI) (1,2) and spiral CSI (3), they are often limited by to a narrow spectral bandwidth and still require multiple radiofrequency (RF) excitations to sufficiently sample k_x - k_y - k_t space. This work introduces a novel single-shot, single-echo spiral acquisition and reconstruction strategy, referred to as kt-spiral to provide efficient single-shot spectral imaging.

THEORY: The signal, $S(t)$, from N expected chemically shift species can be modeled:

$$S(t) = \int e^{i\vec{k}(t)\cdot\vec{r} + \psi(r)t} \sum_{i=1}^N \rho_i e^{i2\pi\Delta f_i t}$$

where $\psi(r)$ is the B_0 field map, $k(t)$ is the k -space position at time t , and Δf_i and ρ_i are the chemical shift and spatial signal distribution of the i^{th} species, respectively. With a known field map, the above equation can be solved by least squares minimization jointing solving for spatial and spectral images. This enables k - t space sampling with the modified spiral trajectory shown in Figure 1, which is designed with a Δk that is η times smaller than required for the nominal field of view (FOV). This effectively oversamples spatial k -space by a factor of η and provides an effective Δt between adjacent spiral rotations that can be utilized for species separation.

METHODS: Experiments assumed or utilized a 4.7T small animal scanner (Agilent, Santa Clara CA). Digital simulations were performed for $[1-^{13}\text{C}]$ pyruvate and downstream metabolites (lactate, alanine, and pyruvate-hydrate) over a range of FOV factors (η) for an idealized (no noise, T_2^* decay or field heterogeneity) and a realistic case ($\Delta B_0 = \pm 25\text{Hz}$, $T_2^* = 15\text{ms}$, 5% complex noise in k -space). Relative root mean square error (RMSE) and metabolite signal ratios were used to assess reconstruction fidelity. To validate the technique, HP pyruvate experiments measuring renal metabolism were performed on a healthy ICR mouse. Five echoes were acquired with $\text{TR/TE}/\Delta\text{TE} = 50/0.6/2.0\text{ms}$, with a readout duration of 30ms. On the basis of simulation results, a spiral trajectory was designed for a FOV of $224 \times 224 \text{mm}^2$, corresponding to an FOV factor $\eta = 7$ in order to efficiently sample k - t space. In-plane resolution was $2 \times 2 \text{mm}^2$, with time frames acquired every 5s. Reconstructions were performed using 1 or all 5 echoes, and accuracy was determined by comparing metabolite dynamics to the five echo acquisition.

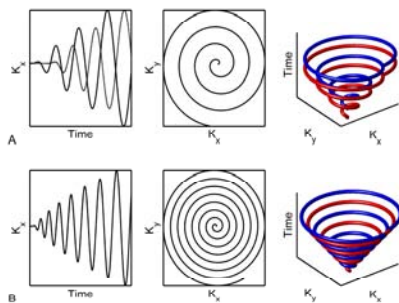


Figure 1. Comparison of k - t trajectories between echo-time shifted spiral interleaves and a spiral trajectory prescribed for an extended FOV.

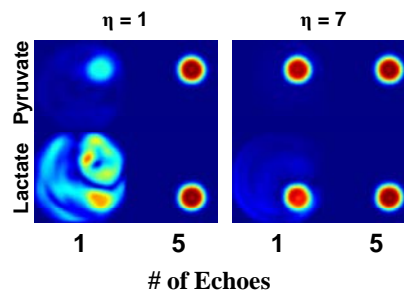


Figure 2. Simulation reconstructed with kt-spiral. For $\eta = 1$, at least four echoes are required to adequately separate frequencies. Larger FOV factors ($\eta = 7$) enable single-shot imaging.

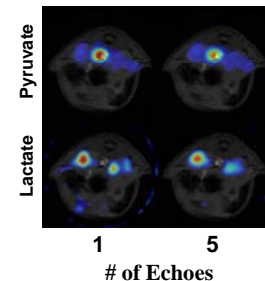


Figure 3. In-vivo results acquired for $\eta = 7$. Data reconstructed with only a single echo agrees well with data using all five echoes.

RESULTS: Digital simulation results indicate that single-shot spectroscopic imaging (i.e. one echo) is possible with a large FOV factor (η) (Fig. 2). Signal ratios using a single-shot for all metabolites were measured to be within 9% for $\eta = 7$, even under realistic conditions (described above). In-vivo metabolite images of pyruvate and lactate acquired with $\eta = 7$ reconstructed using a single-shot or all five echoes can be seen in Fig. 3. Qualitatively, image quality is similar between images reconstructed using a single echo or all five echoes. Quantitatively, the RMSE was less than 4% for both lactate and pyruvate, indicating strong signal fidelity using only a single-shot.

DISCUSSION: Jointly solving for both spatial spectral frequency dimensions (i.e. k - t sampling) enables single-shot imaging of $[1-^{13}\text{C}]$ pyruvate and its metabolic products using a single RF excitation. In-vivo results corroborated simulations and indicate that single-shot 2D spatial/1D spectral imaging is feasible with large FOV factors. By reducing the RF requirements we enable increased flexibility in sampling strategies and reduce scan time, increasing the maximum temporal resolution. Field inhomogeneity and off-resonance effects are corrected for during reconstruction, making k - t spiral robust even in regions of poor field homogeneity.

REFERENCES: [1] Cunningham et al., JMR 2007;187(2):357-362. [2] Larson et al., MRM 2010;63(3):582-591. [3] Josan et al., NMR in Biomedicine 2012;25(8):993-999.

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