Slice Blipped EPI Trajectory for Compressed Sensing Acquisition of 3D Time Resolved Imaging of Hyperpolarized [1-^{13}C]Pyruvate and [1-^{13}C]Lactate

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Purpose: Metabolic MRI via injected hyperpolarized ^{13}C substrates such as [1-^{13}C]pyruvate show promise as minimally invasive prognostic marker of various disease states. Due to the rapid decay of the hyperpolarized signal, clinically viable imaging methods must encode the metabolic signals efficiently. This requirement is compounded for 3D time resolved acquisitions across large fields of view. Spectral-Spatial frequency selective methods[1] represent the most efficient imaging techniques available; however, the size of the imaging volume remains the bottleneck for attainable temporal resolution. This work takes inspiration from Hu and Larson et. al.[1,2] who demonstrated accelerated Echo Planar Spectroscopic Imaging acquisitions through the incorporation of random blips during the readout. Our method employs slice-encoding blips during an echo planar imaging (EPI) readout to pseudo-randomly undersample 3D k-space for acceleration.

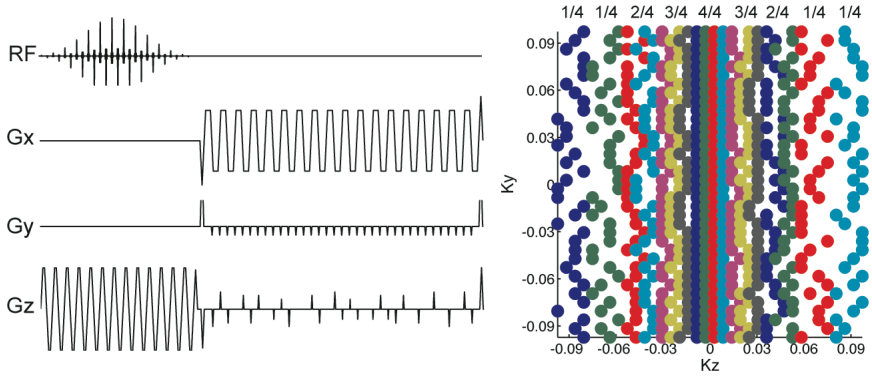

Figure 1: (*left*) Slice blipped EPI gradient waveforms, (*right*) Acquisition schedule. Each color corresponds to a single readout. Sampling densities for each region of Ky/z-space is shown as a fraction of the sub-matrix size. Net undersampling is 50% for 2X acceleration.

Methods: All gradient waveform design and image reconstruction was implemented in Matlab (The MathWorks Inc., Massachusetts). A 3D EPI trajectory was designed to encode a 72×18×18 cm^3 volume with 5mm isotropic resolution using in-house scripts (TR / TE = 56 / 26 ms). Interleaved 18.8 ms spectral-spatial pulses[1], each with 36 slice encoding steps were used for volumetric imaging of [1-^{13}C]pyruvate and [1-^{13}C]lactate (min. temporal resolution ~4s). Undersampling was incorporated into sequence by the addition of slice encoding blips that play out during the ramp portion of the readout gradient (fig 1, left). The acquisition schedule was setup by segmenting Ky/z-space into equally sized regions and assigning sampling density weights for each segment (fig 1, right). For each Ky row and Kz segment, samples were drawn uniformly at random resulting in 2D variable density undersampling of Ky/z-space while fully sampling Kx-space. Each color in figure 1 corresponds to a single readout / TR. Taking the schedule as input, waveforms achieving 2X acceleration were generated and tested *in vivo*. Imaging was performed on a GE MR750 3T MR scanner using a dual tuned T/R ^{1}H/^{13}C rat coil (GE Healthcare, Waukesha, WI). *In vivo* Sprague Dawley (510g) rat images were obtained in accordance with a protocol approved by the institutional animal care and use committee. The net magnetization consumption per volume for pyruvate and lactate was 14% and 88% respectively (net FA = 8°/62°). Two 3mL shots of 80mM pre-polarized [1-^{13}C]pyruvate solutions were and injected over 12s after which imaging commenced. The two injections were ~20 mins apart. For the undersampled acquisition, the flip angle was increased to achieve the same net consumption over fewer excitations and a longer delay was introduced to retain the same temporal sampling of 5s. 2D axial T_2 weighted FSE images were acquired for anatomical reference. A retrospectively undersampled data set was generated by setting k-space values outside of the sampling mask to zero. Both retrospectively and prospectively undersampled data were reconstructed using the SparseMRI toolbox[4] with default regularization parameters (λ=0.01). Sampled data was periodically reinserted between non-linear conjugate gradient iterations to stabilize the reconstruction[3]. A region of interest was traced within the right kidney from the fully sampled data set for simple parametric analysis.

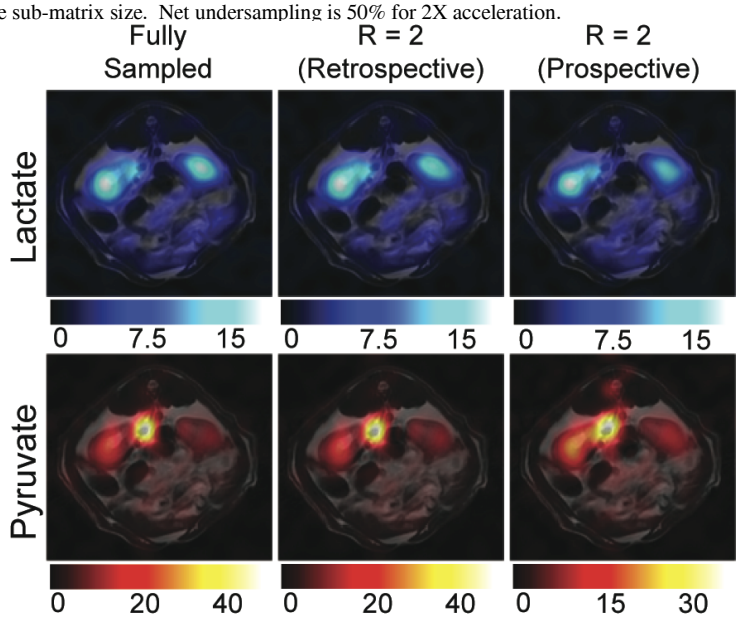

Figure 2: Fully sampled (*left*) and reconstructed images (*center and right*). Scale in arbitrary units. Lactate and pyruvate images were summed through time from the 5-30s and 15-30s respectively. Maximum SNR of the fully sampled summed images was measured to be 46 for lactate and 124 for pyruvate.

Results & Discussion: The images depicted in figure 2 show excellent qualitative agreement between fully and undersampled reconstructions. This is in agreement with the lactate / pyruvate area under curve (AUC) ratios estimated within the right kidney which were 0.161, 0.162 and 0.165 for the fully sampled, retrospectively undersampled and prospectively undersampled reconstructions, respectively. Discrepancies between the fully sampled and prospective acquisition are unsurprising due to potential variance in polarization and injection timing, underscoring that dynamic acquisitions are a crucial component for reproducibility and clinical robustness of ^{13}C applications. The sampling mask employed here was designed conservatively in order to reduce potential eddy current and off resonance artifacts, and is far from optimally incoherent. Future work will explore truly variable density sampling patterns and higher acceleration factors.

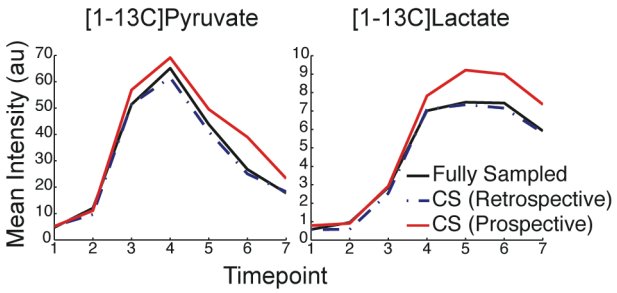

Figure 3: Mean voxel magnitude intensities within a single ROI traced in the right kidney. Intensity values were normalized to reflect the different flip angles on pyruvate and lactate.

Conclusions: In this work, we've demonstrated for the first time an accelerated acquisition scheme that exploits both spectral-spatial excitation and compressed sensing encoding through a novel slice blipped EPI design. Lactate / pyruvate AUC ratios for the fully sampled and the sparse reconstructions were in agreement within 3%.

References: [1] C.H. Cunningham et. al., (2008) JMR 193(1): 139. [2] S. Hu et. al., (2010) MRM 63(2): 312. [3] P.E.Z. Larson et. al., (2011) MRM 65(3): 610. [4] M. Lustig et. al., (2007) MRM 58(6): 1182