A Method for Simultaneous Echo Planar Imaging of Hyperpolarized Compounds

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Introduction

An echo planar imaging sequence for simultaneous dynamic imaging of multiple hyperpolarized ^{13}C compounds is presented. Frequency separation is achieved by spatial mis-registration in the phase-encoded direction by the appropriate choice of echo spacing. Excitation of only two resonances is achieved with an optimized multiband RF waveform. Arbitrarily large chemical shift dispersions can be simultaneously encoded by allowing for spatial aliasing. The sequence has been used to image hyperpolarized [1-^{13}C] pyruvate and [1-^{13}C] lactate (Δf = 390 Hz) as well as hyperpolarized (bis-1,1-(hydroxymethyl)-[1-^{13}C] cyclopropane –d8) (HP001) and [1-13C] lactate (Δf = 5130 Hz) after co-infusion of hyperpolarized HP001 and pyruvate. Dynamic imaging is demonstrated in a transgenic mouse model.

Methods

A flyback EPI sequence using N_{etl} readout lobes equally spaced by t_{esp} was implemented (Figure 1). Planar k-space data was acquired in N_{int} interleaves using echo shifting for mitigation of phase ghosting errors [1]. With the transmitter at the mean frequency of the two resonances, the following relation holds:

$$t_{esp} = \frac{2(\Phi + N_{alias})N_{int}}{\Delta f}$$

where N_{alias} is the number of spatial aliases, Δf is the chemical shift dispersion of the two resonances, and Φ is the fractional field of view the images are shifted. Setting Φ =1/4 generates images of f_1 and f_2 side by side on the phase encoded dimension as long as the phase field of view is at least twice the spatial extent of the object. N_{alias} is a free parameter that can be set greater than zero for large Δf while still maintaining a practical t_{esp}. Different spectral-spatial waveforms were developed [2,3] for each experiment. A 13 ms waveform giving a nominal flip angle of 7.5° to pyruvate, 15° to lactate, and 0° to alanine and pyruvate-hydrate was used for the pyruvate injection. For the HP001 and pyruvate injection, a second 19 ms waveform was developed giving nominal flip angle of 5° to HP001, 15° to lactate, and 0° to pyruvate, hydrate, and alanine. For pyruvate / lactate imaging, t_{esp} = 5.2 ms, N_{alias} = 0. For lactate / HP001, t_{esp} = 5.2 ms, N_{alias} = 3. TE_1 = 18ms, TR = 80ms, and N_{int} = 4 for both acquisitions.

The sequence was tested in a single 2D slice in the coronal plane. Hyperpolarized pyruvate and combined pyruvate / HP001 were polarized [3] in an Oxford Instruments Hypersense DNP polarizer, dissolved, neutralized, and injected into a transgenic prostate cancer tumor-bearing mouse over a 12 s. A 32×32 grid over a 10 cm FOV was acquired every 3 seconds after injection of the hyperpolarized solution. Acquisition time per slice was $TR \times N_{int}$ = 320 ms. A readout bandwith of ± 5 kHz was used.

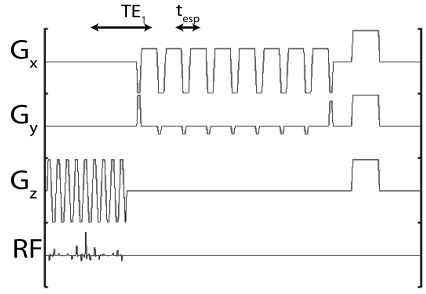

Figure 1: Pulse sequence showing a single *TR*.

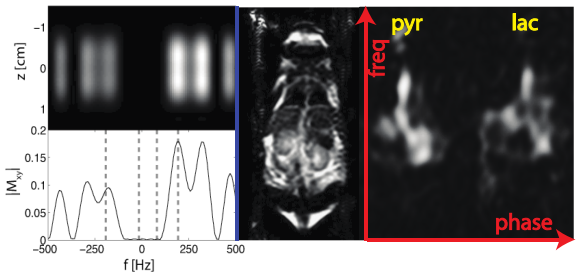

Figure 2: Spectral spatial profiles of the RF pulse (left), a coronal FSE localizer (center), and lactate / pyruvate images from a single time point (right).

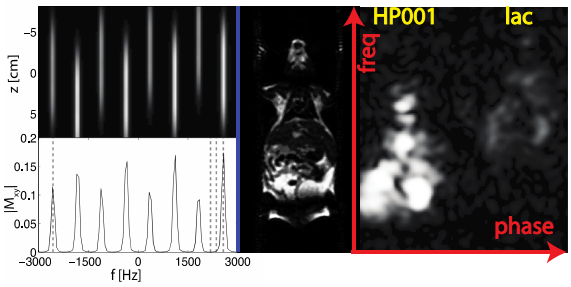

Figure 3: Same as the above figure but pulse profile and images of the pyruvate and HP001 experiment. The pulse sequence dynaically images HP001 and lactate.

Results

Figures 2 and 3 show representative images of the two experiements. In both cases, the two resonances were spatially separated and non-overlapping in the phase-encoded dimension (L/R). A shift was evident in the readout direction (A/P), particularly with lactate / HP001 (Figure 3). Both phase and frequency shifts can be accounted for by an image-domain translation proportional to frequency difference and to the reciprocal of the sampling rate.

Conclusion

Simultaneous encoding of two hyperpolarized resonances is demonstrated with an EPI imaging sequence. A simple reconstruction was possible using image domain shifts. Similar to the IDEAL method, this imaging sequence requires a minimum of two phase encodes per frequncy point. However, unlike IDEAL, the inclusion of EPI phase blips gives more than two phase encodes per *TR*, thus increasing imaging speed. Although not practical for the small chemical shifts encountered in proton MRI, this method shows promise in ^{13}C imaging where the frequency dispersions are large and the gradient integral requirements force the echoes to be spaced further apart.

References [1] D. A. Feinberg et al, MRM 32 (1994), 535-9. [2] P. E. Z. Larson et al, JMR 194 (2008), 121-7. [3] A. B. Kerr et al, 16th ISMRM, 226. [2] J. H. Ardenkjaer Larson, et al., PNAS 100 (2003), 10158-63. [3] D. M. Wilson, et al., JMR 205 (2010), 141-7

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