13C multi-spectral 2D rosette imaging

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Introduction

The recent advent of hyperpolarization techniques has generated the potential for significant improvement in our capacity to follow real time metabolism. Unlike PET, which only shows the area where glucose is consumed, hyperpolarized molecules can pass the ^{13}C labels to their downstream metabolites, which can then be individually visualized through MRI. For example, living cells convert injected pyruvate (Pyr) to lactate (Lac), alanine (Ala), and Bicarbonate (Bic), and the rise and decay of all four metabolite concentrations can be monitored *in vivo* using spectroscopic acquisitions [1]. Spatial and spectral encoding of ^{13}C data is typically achieved using CSI-type techniques; such techniques, however, are not optimal for the particularities of hyperpolarized signals as they have limited spatial and temporal resolution. In this paper, we explore the feasibility of achieving a considerable speed-up of data acquisition through the use of a 2D rosette sequence [2]. We demonstrate through phantom experiments that all frequencies pertinent to the *in vivo* metabolism of Pyr can be properly reconstructed using single or multiple shot rosette trajectories.

Methods

A 2D rosette sequence [2] was implemented on a GE 1.5T scanner at the ^{13}C frequency. Typical k-space coverage for rosette trajectories can be expressed as $k_x = k_{\max} \cdot \sin(2\pi f_1) \cdot \cos(2\pi f_2); k_y = k_{\max} \cdot \sin(2\pi f_1) \cdot \sin(2\pi f_2)$. Here f_1 represents the frequency of oscillation and f_2 represents the frequency of rotation for the k-space trajectory. Reconstruction was performed using a 2D convolution gridding algorithm in MATLAB and the density compensation function was calculated using a variation of the Jacobian [3]. Simulations were performed to estimate the optimal data acquisition parameters (f_1, f_2, BW, TR etc), by calculating the SNR of images reconstructed from objects with known analytical Fourier transforms and given chemical shifts sampled on various rosette trajectories. Simulations indicated that given our gradient performance, for Pyr and its downstream metabolites, a choice of f_1=321Hz and f_2=76.5 Hz was demonstrated to produce optimal SNR and spatial resolution. Other acquisition parameters were 32 arms (512 points per arm), a bandwidth of 15.25 kHz, TR= 5 s and 4 averages (to match the acquisition time of a standard 16 x 16 FID CSI sequence). Partial k-space coverage can be seen in Figure 1, which presents ¼ of the total acquisition (8 arms). Four ^{13}C labeled phantoms containing 1.7M of Lac, 1.1M of Pyr, 900mM of Bic and 1.37M of Ala were built, and scanned using a $^{13}C/^{23}Na$ birdcage coil. Figure 2a is a proton image showing the relative spatial positions of the ^{13}C phantoms and Figure 2b presents the spectrum of the phantoms. The SNR of the rosette images was then compared to the SNR of a standard FID CSI sequence acquired at identical TEs, TRs and total acquisition times. The FID CSI data was zero padded to 64x64 for reconstruction, while the 2D rosette sequence was acquired at true 64 X 64 resolution.

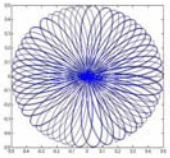

Figure 1: *Typical k-space coverage of ¼ total acquisition*

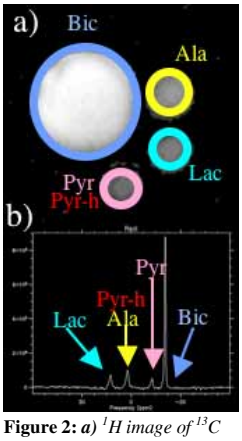

Figure 2: ***a)*** *^{1}H image of ^{13}C phantoms used and their arrangement* ***b)*** *spectrum of C-13 phantoms in a)*

Results and Discussion

Figure 3 shows the ^{13}C images of our experimental setup overlaid on the proton images; Fig 3a through 3d represents the data reconstructed at the Lac, Ala, Pyr and Bic frequencies, respectively. Good spectral selectivity is exhibited by this sequence, as all four metabolites could be individually reconstructed. In Fig 3b both the Ala and Pyr phantoms are visible, a direct result of the spectral overlap between Ala and pyruvate hydrate (Pyr-h, in equilibrium with Pyr) seen in Figure 2b. The SNR of the images acquired using the 2D rosette sequence was comparable to the SNR of a standard FID CSI sequence, though the true resolution of the rosette was 4X higher. Our extended acquisition time of 21 minutes was due to the long repetition time (5 sec) used to accommodate for the vastly different phantom T_1s (~5s for Lac to >1 min for the rest), the short T_2^*(<60ms), and the inherently low signal from the non-polarized ^{13}C phantoms. Given the much higher signal and the longer T_2* of *in vivo* hyperpolarized Pyr, we estimate that a 64X64 2D rosette slice, allowing the reconstruction of all 4 frequencies of interest, can be acquired in a single shot with f_1=321Hz, f_2=81 Hz and a BW of 31.25 kHz (16384 samples) with a total acquisition time of less than 300ms. By comparison, a standard 64X64 CSI data acquisition (at the same TR of ~300ms) would take ~20 minutes. One of the unique characteristics of a rosette sequence is the oversampling of the center of k-space at different time points, resulting in destructive interference of the off-resonant frequencies. 2D rosette sequences have been previously explored for ^{1}H imaging, but the strong sensitivity to B_0 inhomogeneities have limited their applications [4]. Given the significantly lower ^{13}C gyromagnetic ratio, artifacts due to B_0 inhomogeneities are less pronounced, thus making rosette imaging more practical.

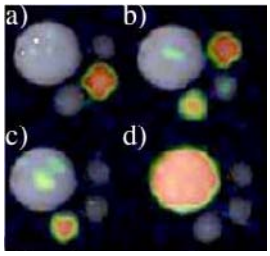

Figure 3: *Reconstructed 2D rosette image overlayed on proton image for* ***a)*** *Lac at +150 Hz, SNR=37,* ***b)*** *Ala at +34 Hz, SNR=32,* ***c)*** *Pyr at -155 Hz, SNR=16.8 and* ***d)****Bic at -219 Hz, SNR=65*

Conclusion

Multiple resonant frequencies were successfully acquired and reconstructed using a 2D rosette imaging sequence. The resulting images had comparable SNR and higher spatial resolution than a standard FID CSI sequence with matched acquisition time. Temporal resolution is paramount when following the metabolism of the hyperpolarized compounds *in vivo*, due to the fast decay of the hyperpolarized signals. The 2D rosette sequence shows significant promise in its application to hyperpolarized ^{13}C compounds; our calculations indicate that given the increased SNR and higher T2* reported for in vivo hyperpolarized pyruvate applications, it will be possible to acquire single shot images that contain all the spectral information for Pyr and its down-stream metabolites. In the phantom study it was possible to reconstruct the phantoms with only 4 arms instead of the 32, but at the cost of spatial resolution. This tradeoff can be used to obtain high temporal resolution images for hyperpolarized ^{13}C compounds.

References: 1. Golman, K. et al. PNAS 103(30):11270, 2006. **2.** Noll, D.C. IEEE Trans Med Imaging 16(4):372,1997. **3.** Hoge, R.D. et al. MRM 38:117-128,1997 **4.** Noll, D.C. et al. MRM 39(5):709,1998.

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