Super Stimulated-Echo Preparation for Hyperpolarized 13C Metabolic Imaging

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Introduction: The stimulated-echo (STE) can be used to provide high sensitivity to diffusion and flow (1). We have recently applied a STE acquisition mode (STEAM) to hyperpolarized [1-^{13}C]pyruvate metabolic imaging and found improved tumor contrast (2). The STE distinguishes whether [1-^{13}C]pyruvate is converted to [1-^{13}C]lactate within the tissue or whether the [1-^{13}C]lactate was produced elsewhere and flowed into the tissue, which can confound metabolic data interpretation. However, the STEAM suffered from an inherent 50% SNR loss as well as motion artifacts during the 8 sec 3D EPSI spectroscopic acquisition. To address these problems, we propose a super stimulated-echo (3-5) magnetization preparation scheme for improved SNR and reduced motion artifacts.

Methods: The super stimulated-echo (sSTE) uses a RF pulse train instead of the two 90º pulses used for a conventional STE (3-5). This improves the SNR by storing the magnetization in a square-wave pattern on the longitudinal axis following the STE encoding, as opposed to the more lossy sinusoidal storage of conventional encoding (Fig. 1). In our prep scheme, the STEAM refocusing pulse, which is also lossy, was replaced by the encoding pulse train. This leaves the magnetization longitudinal and refocused but still prepared with the diffusion and flow sensitivity. It can then be followed by any acquisition.

The pulse train was designed using conventional inversion pulse design methods with N samples and a bandwidth of 1/2ΔT, and then spacing the samples with a separation of ΔT. This has a profile consisting of repetitions of the inversion band, which maintains the motion sensitivity of a STE. Using a gapped adiabatic pulse (6) design improves the B_1 sensitivity of the pulse train. The prep pulse scheme was followed by a 3D MRSI with compressed sensing as described in (7). This was initiated 30-35 sec following the start of the 80 mM hyperpolarized [1-^{13}C]-pyruvate injection. The prep pulse used a hyperbolic secant (sech) envelope with N=18, ΔT = 3ms, TM = 1s, and b ≈ 53 s/mm^2.

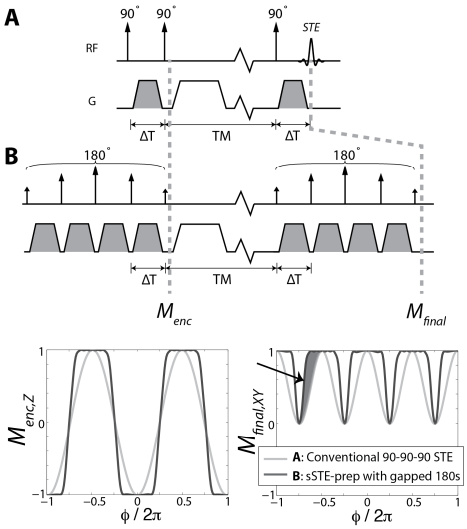

Figure 1: (A) Conventional STE and (B) sSTE-prep pulse sequences, with the corresponding magnetization profiles. The sSTE-prep has more efficient encoding and refocusing, with a predicted 60% SNR increase (from shaded area in M_{final} profile).

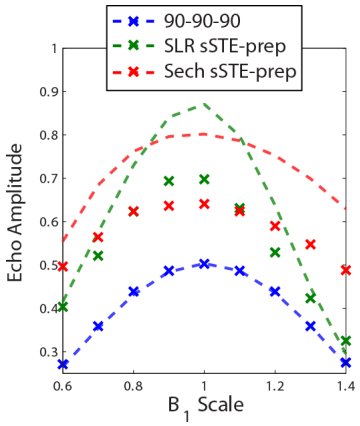

Figure 2: Simulated (dashed) and experimental (x) phantom results, showing both the improved SNR and B_1 insensitivity of the sech sSTE-prep scheme. The sech design is relatively constant over a ± 20% B_1 range when compared to STEAM and an SLR inversion design. The experimental SNR improvements were less than expected due to diffusion-weighting in the phantom.

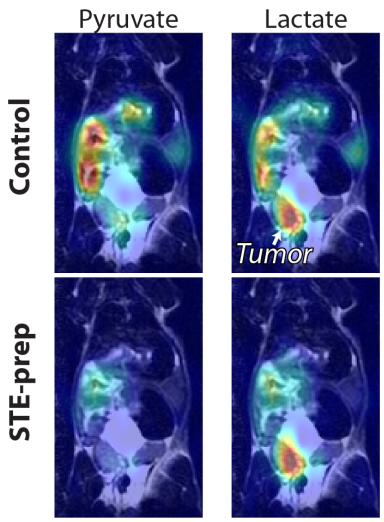

Figure 3: Representative transgenic prostate tumor model data. The sSTE-prep approach (sech pulse) clearly highlights the tumor lactate and suppresses lactate elsewhere. This was also seen in a transgenic liver tumor model (data not shown).

Results: Simulated and phantom experiments demonstrated improvements in signal, as well as the improved B1 response of the sech sSTE-prep design (Fig. 2). Figures 3 and 4 show improved prostate tumor lactate contrast in vivo, which also had better signal than previous STEAM experiments (2).

Conclusion: The sSTE-prep scheme increases the SNR and B_1 robustness when compared to STEAM for diffusion and perfusion-sensitive hyperpolarized ^{13}C metabolic imaging. Initial results show substantially improved prostate tumor contrast.

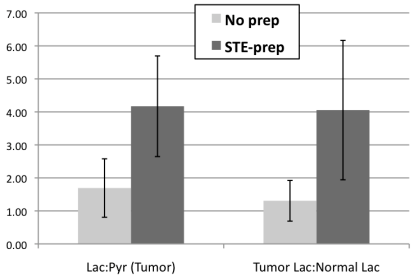

Figure 4: Average data across 4 TRAMP mice showing the increased lactate:pyruvate ratio in the prostate tumors, as well as the improved lactate contrast between tumor and normal tissue (max).

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