Ramp-Sampled, Symmetric EPI for Rapid Dynamic Metabolic Imaging of Hyperpolarized ^{13}C Substrates on a Clinical MRI Scanner

Jeremy W Gordon[1], Sonam Machingal[1], John Kurhanewicz[1], Daniel Vigneron[1], and Peder Larson[1]
[1]*Radiology & Biomedical Imaging, UCSF, San Francisco, CA, United States*

Target Audience: Researchers interested in fast hyperpolarized ^{13}C MRI and techniques for clinical translation.

Introduction: Hyperpolarization (HP) of ^{13}C substrates has enabled rapid and non-invasive imaging of metabolism, but the need for spectral encoding places limitations on the temporal resolution and the acquisition approach. In conjunction with spectral-spatial (SPSP) RF pulses, flyback echo planar imaging[1,2] (EPI) has been applied to acquire metabolite maps in a single RF excitation with sub-second temporal resolution. However, the lower ^{13}C gyromagnetic ratio results in reduced scan efficiency and longer echo times (TE) that exacerbate EPI-related image artifacts. Translating this technique to clinical ^{13}C imaging will require further improvements in scan efficiency in order to improve SNR and enable rapid, robust and dynamic metabolic imaging in-vivo. To that end, we developed a symmetric, ramp-sampled EPI sequence for HP ^{13}C imaging that can reduce the echo-spacing and TE, improve SNR, and reduce blurring, chemical shift, and motion related artifacts with the goal of translation for clinical studies.

Methods: The new sequence was built off a product GE EPI sequence to incorporate its performance and safety features. It was modified to enable broadband ^{13}C capability, tailored SPSP RF, variable flip angle (VFA) schedules, and multi-frequency dynamic imaging within one instance. ^{13}C phantom studies were used to compare SNR and scan parameters between flyback and symmetric EPI. Chemical species were individually excited with a singleband SPSP excitation, and data were acquired using either a flyback or symmetric, ramp-sampled EPI readout. The reference scan for the symmetric EPI sequence was modified to allow signal averaging, improving the phase estimation required to correct the symmetric readout for any timing delays between even and odd lines of k-space[3]. Scan parameters were otherwise identical for both acquisitions (1s TR, 96×96 mm FOV, 32×32 matrix, 60 averages, 60˚ flip). To assess the feasibility of symmetric, ramp-sampled EPI in-vivo, dynamic data were acquired with HP [1-^{13}C]pyruvate (80ms TR, 96×96 mm FOV, 32×32 matrix, 2s delay between frames) in the study of renal metabolism. Data reconstruction was performed offline using the GE Orchestra toolbox in Matlab, and all experiments were performed on a GE MR750 3T scanner.

	TE	Echo Spacing	SNR
Flyback EPI	57.9 ms	2.24 ms	54.1 +/- 2.8
Symmetric EPI	45.2 ms	1.74 ms	98.7 +/- 7.8
Ramp sampled, Symmetric EPI with Partial Fourier	26.4 ms	1.14 ms	108.1 +/- 8.5

Table 1. *Phantom comparison between flyback and symmetric EPI. Note the increase in SNR and concomitant decrease in TE with ramp sampling and a symmetric readout.*

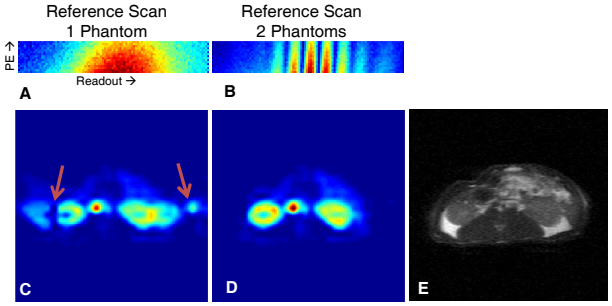

Figure 1. *The impact of the reference scan on symmetric EPI image quality. With only a single ^{13}C phantom, k-space is slowly varying (A) and provides a poor phase correction for metabolite images (C, red arrows). With two phantoms, k-space is modulated (B), improving image quality and removing ghosting artifacts (D). An anatomical axial image of the kidneys is provided for reference (E).*

Results & Discussion: Results from the ^{13}C phantom study (**Table 1**) indicate that the symmetric, ramp-sampled EPI can improve SNR by nearly a factor of two. However, acquiring a quality reference scan is critical for image quality in symmetric EPI and is difficult to acquire during the HP ^{13}C experiment due to the transient magnetization. Using two ^{13}C urea phantoms separated in the readout direction leads to modulation in k-space (**Fig. 1B**), providing an improved estimate of the phase correction. In-vivo results (**Fig. 1D**) illustrate the image quality that symmetric EPI can provide, while the absence of ghosting artifacts in the dynamic experiment (**Fig. 2**) indicates that the ^{13}C reference scan from thermally polarized phantoms is capable of phase correction for in-vivo applications. With the ability to retroactively apply reference scan corrections, a reference scan can also be directly obtained from the remaining in-vivo magnetization immediately following a HP experiment.

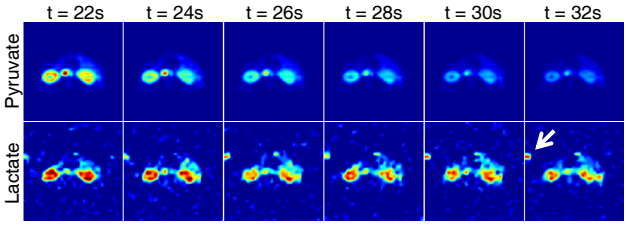

Figure 2. *In-vivo dynamic data obtained using the ramp sampled, symmetric EPI sequence. The improved SNR and spatial resolution (3x3 mm) of symmetric, ramp-sampled EPI enables renal structure to be distinguished in the pyruvate maps, and the lack of ghosting indicates the proposed ^{13}C reference scan is suitable for in-vivo applications. The white arrow in the lactate frame points to the ^{13}C urea syringe excited by the off-resonant passband for this SPSP pulse.*

Conclusion: Ramp-sampled, symmetric EPI provides a fast, robust and clinically efficacious way to acquire hyperpolarized ^{13}C data. The significant SNR increase enables improved temporal and spatial localization and increased scan coverage. The gains of this efficient sampling, combined with partial Fourier methods, will be crucial for large matrix sizes required for human-sized FOVs. This pulse sequence is well suited for clinical dynamic imaging of hyperpolarized substrates as it leverages the product reconstruction engine to reconstruct ^{13}C metabolite maps on the scanner in real time, and can be easily incorporated into the existing workflow.

References: [1]Cunningham et al., JMR 2008. 193(1). [2]Reed et al., JMR 2012. 217(0). [3]Bruder et al., MRM 1992. 23(2).