Combined Parallel and Partial Fourier MR Reconstruction for Accelerated Hyperpolarized ^{13} *In Vivo* MRSI

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Introduction: Hyperpolarized ^{13}C techniques exploit dynamic nuclear polarization (1) to increase the nuclear polarization of ^{13}C nuclei by several orders of magnitude compared to thermal equilibrium. Hyperpolarized carbon-13 resonances decrease in time due to RF saturation, T1 decay and metabolism, which places a tight constraint on the MR acquisition method and time when using ^{13}C labeled compounds. With high intrinsic SNR and need for imaging speed, parallel MRI acquisitions are well-suited to hyperpolarized ^{13}C applications (2). In particular, self-calibrating parallel MR techniques are especially attractive given that they do not require an external sensitivity reference, which can be challenging for an *in vivo* hyperpolarized ^{13}C experiment. Reference (3) describes a self-calibrating SENSE acquisition for ^{13}C imaging of a mouse. We demonstrate the feasability of achieving an additional 39% reduction in scan time by combining self-calibrating parallel MRI techniques with a partial Fourier acquisition.

Theory: We employ a phase-constrained version of the generalized encoding matrix (4) reconstruction and extend it for use in spectroscopy. This reconstruction is based on a generalized form of SENSE (5, 6), where the image is reconstructed from the encoding matrix by computing the Moore-Penrose pseudoinverse. The combined parallel imgaing and partial Fourier reconstruction is implemented as in Ref (4) by requiring the reconstructed data to be real. The application of the phase constrained reconstruction to MR spectroscopy requires three extensions to this theory: **1.** The reconstruction equation is frequency-dependent and is applied independently to each frequency. **2.** Phase variations induced by the spectroscopic acquisition require a different self-calibrating sensitivity reference to be extracted *for each frequency*. **3.** Spectral processing (such as line broadening) is achieved by forming reconstructed component coil images as an intermediate step.

Methods: Normal Sprague-Dawley rats were imaged on a 3T MRI scanner. A clamshell ^{13}C body exciter was used for transmit and a custom-built 8-channel ^{13}C coil array was used for signal reception (Fig 1). The array contained 2 parallel paddles, each with 4 elements for a total of 8 channels. The coils measured approximately 5 x 10 cm with overlap to remove nearest-neighbor coupling. Samples of 32 ml [1-^{13}C] pyruvic acid (Isotec Inc., Miamisburg, OH) and 15 mM OX63 trityl were polarized and dissolved using a Hypersense DNP polarizer (Oxford Instruments). 2.5 mL boluses of 100 mM pyruvate were injected through a tail vein catheter over a period of 12 s, followed by a 0.5 cc normal saline flush. A 3D echo-planar spectroscopic imaging sequence with flyback gradient EPSI was used. Each flyback readout yielded 16 spatial points and 59 spectral points, with a spectral bandwidth of 581 Hz. Images were acquired with 0.8 cm isotropic spatial resolution. Animals were placed supine and phase encode directions were placed in the foot-head and dorsal-ventral directions. Baseline matrix size included 30 x 10 phase encode steps. A central 6x6 region of k-space was fully-sampled in order to obtain an autocallibrating sensitivity reference. Half of the remaining k-space lines were removed in order to implement partial fourier imaging. The remaining lines were further undersampled by a factor of 2 (Fig 2). Images were reconstructed using Matlab and a generalized form of SENSE described above.

Fig 1

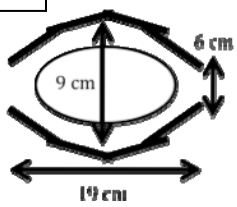


Fig 2

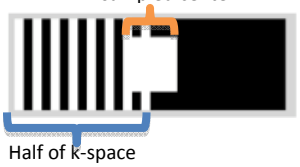
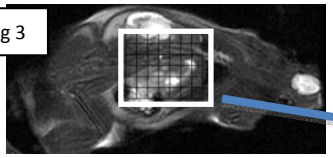


Fig 3



Blue: Full acquisition (30 s)

Green: Parallel reconstruction (13 s)

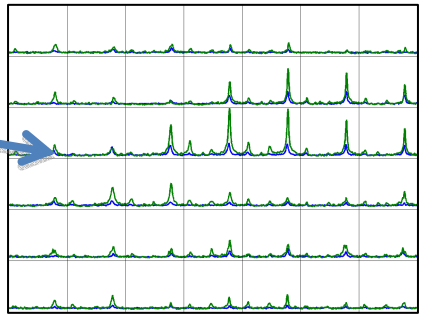
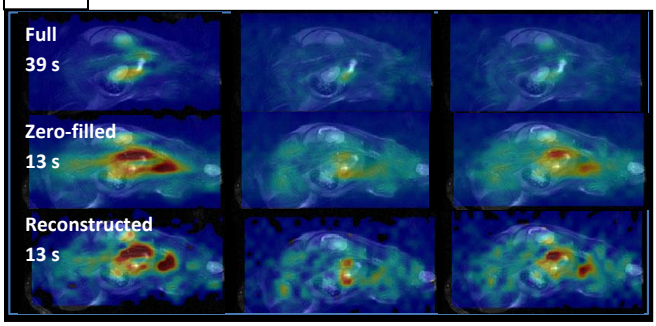


Fig 4



Results and Discussion. An undersampled EPSI acquisition was obtained according to the sampling pattern shown in Fig. 2. For each phase encode point, there were 16 spatial frequency encode points and 59 spectral points. Acquisition time was 13 s. A fully phase-encoded acquisition was also obtained (30 x 10 phase encode steps, acquisition time 39 s). Fig 3 shows selected voxels from a coronal MRSI slice for the undersampled and reconstructed (green) and fully-encoded (blue) acquisition. The undersampled acquisiion shows increased signal as expected for the shorter acquisition which averages less of the temporal decreases due to uptake, metabolism, T1 and washout. There are voxels where the full acquisition shows no significant metabolite signal but the metabolites were detected using the accelerated acquisition. Fig. 4 shows color maps corresponding to peak integrals of pyruvate, lactate and alanine. Alanine and lactate signals have been multiplied by a factor of 3. The full acquisition (top row) shows low overall signal, with signal concentrated only in the kidneys. The zero-filled accelerated data has higher signal, but suffers from spatial blurring. The reconstructed undersampled data retains higher signal compared to the full acquisition, but recovers higher spatial resolution.

Summary and Conclusion We have applied a combined partial Fourier and self-calibrating parallel MRI reconstruction to the acquisition of hyperpolarized ^{13}C spectroscopic imaging in a rat. A 30 x 10 x 16 matrix of 4800 spectroscopic voxels may be obtained in 13 s. The combined partial Fourier and parallel reconstruction required 104 phase encode steps, compared to 168 phase encode steps if the partial Fourier component was not included. This represents an added reduction in scan time of 39%. The effect of undersampling on the zero-filled unreconstructed image is primarily a decrease in spatial resolution, without significant visible spatial aliasing. This is a reflection of the fact that the fully-sampled 6 x 6 center of k-space is a relatively large fraction of the acquisition. The lost spatial resolution is recovered following image reconstruction. Several adjustments to theory are required to apply partial fourier imaging to an echo planar spectroscopic imaging acquisition, which been explored in simulation (not shown). Additional speed gains from the partial Fourier acquisition partially mitigate the time required to obtain a fully-sampled center of k-space. Although MRSI images are shown here, these techniques are equally applicable to imaging-based approaches to hyperpolarized ^{13}C. The 24 x 8 x 16 matrix size explored in this work is close to that required for human imaging *in vivo,* and this work demonstrates the feasibility of acquiring such images within the duration of a single breath hold.

Acknowledgments K. Scott for technical assistance, funding from NIH grant P41EB013598 and UC Discovery grant ITLbio 178688 with GE Healthcare. **References** **1.** Ardenkaer-Larsen et al PNAS 2003 100:10158 **2.** Tropp et al JMR 2010 208:171 **3.** Arunachalama et al NMR Biomed 2009 22:867 **4.** Willig-Onuwachi JMR 2005 176:187 **5.** Pruessmann et al MRM 1999 42:952 **6.** Sodickson et al Medical Physics 2001 28:1629