Compressed Sensing for Resolution Enhancement of Hyperpolarized Carbon-13 Flyback 3D-MRSI

S. Hu[1,2], M. Lustig[3], A. P. Chen[1], J. Crane[1], A. Kerr[3], D. Kelley[4], R. E. Hurd[4], J. Kurhanewicz[1,2], S. J. Nelson[1,2], J. M. Pauly[3], and D. B. Vigneron[1,2]

[1]Dept. of Radiology, University of California at San Francisco, San Francisco, CA, United States, [2]UCSF & UCB Joint Graduate Group in Bioengineering, San Francisco, CA, United States, [3]Dept. of Electrical Engineering, Stanford University, Stanford, CA, United States, [4]GE Healthcare, San Francisco, CA, United States

Introduction: High polarization of nuclear spins in liquid state through dynamic nuclear polarization has enabled the direct monitoring of ^{13}C metabolites in vivo at very high SNR [1], allowing for rapid assessment of *in vivo* metabolism [2]. The high SNR provided by this hyperpolarization technique makes high-resolution ^{13}C 3D-MRSI feasible. However, the ^{13}C T1's of <1 minute limit the array size and thus spatial resolution and coverage possible with conventional phase-encoding. In this project, we have applied compressed sensing (CS) methods to exploit the inherent sparsity of ^{13}C spectra and achieve higher spatial resolution without increasing acquisition time. The design and testing of CS techniques for a flyback ^{13}C 3D-MRSI sequence are presented. Spectral k-space was pseudo-randomly undersampled using a blipped scheme, achieving the incoherent sampling requirement of CS.

Theory and Design: Compressed sensing, a recent advance in mathematical theory, has opened the door for accurate signal reconstruction from sub-Nyquist sampling [3-4], with the constraints that the data have a sparse representation in a transform domain, the aliasing from undersampling be incoherent in that transform domain, and a non-linear reconstruction be used to enforce both sparsity of the data and consistency with measurements [5]. Previous successes in the application of CS to MRI [5,6], coupled with the inherent sparsity of hyperpolarized spectra, makes hyperpolarized ^{13}C a logical choice as a new application. Exploiting the sparsity of hyperpolarized spectra to satisfy the first two constraints listed above was the key design challenge, which we met by employing a blipped scheme that pseudo-randomly undersamples in the spectral domain (k_f) as well as in the spatial domain (k_x). As shown in Figure 1, we added x-axis blips during the flyback readout to hop between adjacent k_x lines, in effect collecting two pseudo-random undersampled sets of k_f-k_x data during a single readout, thus doubling the k_x coverage without increasing acquisition time. Because hyperpolarized spectra have a sparse representation in the wavelet domain, the first constraint of having sparse data was satisfied. In addition, by using a pseudo-random pattern of blips, we fulfilled the second constraint of generating incoherent aliasing. The third constraint was met by using the non-linear reconstruction described in [5].

Methods: All experiments were performed on a General Electric EXCITE 3T (Waukesha, WI) MR scanner equipped with 40 mT/m, 150 mT/m/ms gradients and a broadband RF amplifier. We acquired 3D-MRSI data from a spherical ^{13}C phantom as well as from a transgenic mouse model of prostate cancer using a specialized pulse sequence (Figure 1) based on a previously described double-spinecho sequence [7]. For phantom studies, the acquisition parameters were: 10 degree flip angle, TE = 140 ms, TR = 2 s, FOV = 8x8 cm, and 16x8 spatial resolution. We compared a normal acquisition with an undersampled one that had half the phase encodes and thus half the scan time. The mouse experiment acquisition parameters were: variable flip angle, centric phase encoding order, TE = 140 ms, TR = 215 ms (total acquisition time of 14 s), and FOV = 4x4 cm. Due to the time constraints following the injection of the hyperpolarized pyruvate, the in-vivo comparison was between an 8x8 normal acquisition and a 16x8 undersampled acquisition. For this *in vivo* experiment, we achieved ~23 % liquid state polarization of [1-^{13}C]pyruvate using a DNP polarizer. We injected ~300µL (~80 mM) samples into the mouse through a surgically placed jugular vein catheter. Custom built, dual-tuned $^{1}H/^{13}C$ transmit/receive coils were used for all phantom and animal experiments.

Results: Figure 2 shows a comparison of normal and CS undersampled phantom acquisitions. For the CS acquisition, due to the denoising properties of the CS reconstruction, there was no loss in the final peak SNR (normal – 63.2, undersampled – 64.8) even though scan time was reduced. The resulting metabolite ratios, which were calculated as averages from voxels with little or no partial voluming, showed excellent agreement (normal: 0.549 ala/lac, 0.462 pyr/lac, 0.427 pyr-H_2O/lac; undersampled: 0.547 ala/lac, 0.467 pyr/lac, 0.405 pyr-H_2O/lac). Figure 3 shows a comparison of the normal 8x8 and undersampled 16x8 mouse acquisitions. Even though the voxel size was halved for the undersampled acquisition, the final peak SNR was 107.4 (normal – 133.9). The large, relatively homogenous tumor in this particular mouse permitted lactate/pyruvate ratio comparisons despite the differing resolutions. The ratios, calculated from tumor voxels, demonstrated excellent agreement (normal: 2.44 lac/pyr, std = 0.432, 16 voxels; undersampled: 2.51 lac/pyr, std = 0.588, 14 voxels).

Discussion: We developed a blipped design for applying compressed sensing to flyback hyperpolarized ^{13}C 3D-MRSI and demonstrated improved spatial resolution for phantom and mouse studies. It is important to note that this initial design exploits 2D sparsity and we expect through future work that 3D sparsity can be exploited to yield further performance improvements. We believe that this acceleration technique can be important for future in-vivo applications of hyperpolarized ^{13}C where increased spatial coverage and/or resolution are needed.

References: [1] Ardenkjaer-Larsen et al, Proc Natl Acad Sci USA 100:10158-10163(2003) [2] Golman et al, Proc Natl Acad Sci USA 100:10435-10439(2003) [3] Candes et al, IEEE Tran Info Theo 52:489-509(2006) [4] Donoho DL, IEEE Tran Info Theo 52:1289-1306(2006) [5] Lustig et al, "Sparse MRI", manuscript accepted by MRM [6] Lustig et al, Proc ISMRM 2420(2006) [7] Cunningham et al, J Magn Reson 187:357-362(2007)

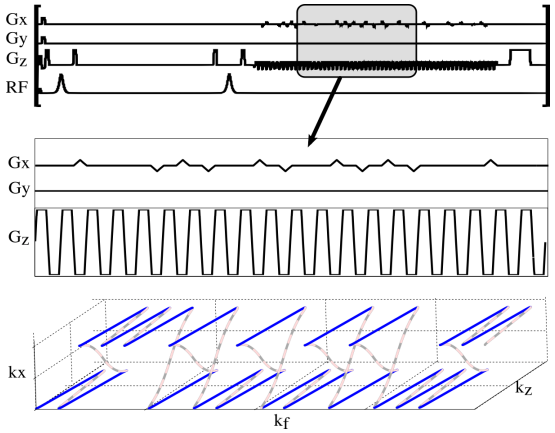

Figure 1: *The pulse sequence used in this study for compressed sensing acquisitions and its associated k-space trajectory*

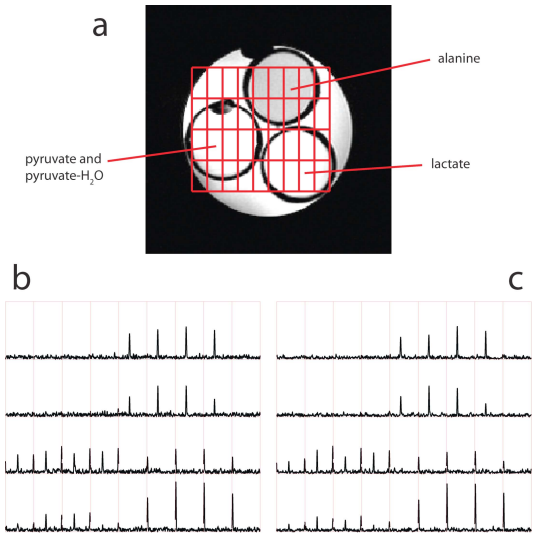

Figure 2: *Phantom normal/compressed sensing comparison: a) T2-weighted image b) Normal 16x8 c) Undersampled 16x8 (half the phase encodes).*

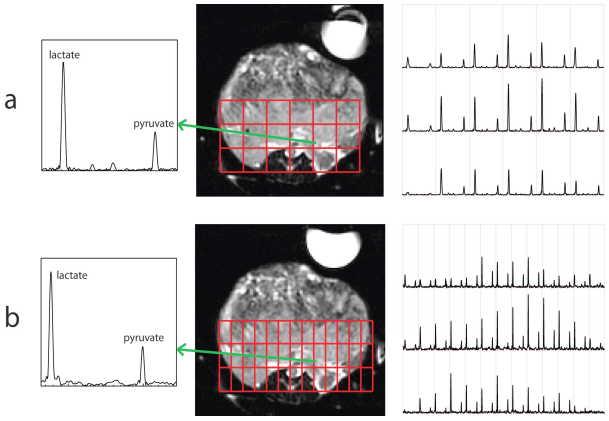

Figure 3: *Mouse normal/compressed sensing comparison showing injected C-13 pyruvate and metabolic products: a) Normal 8x8 b) Undersampled 16x8 with compressed sensing.*