Improved Temporal Resolution for Hyperpolarized ^{13}C 3D Dynamic MRSI with Compressed Sensing

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Introduction: Time-resolved spectroscopic imaging following injection of hyperpolarized [1-^{13}C]-pyruvate can provide valuable and detailed metabolic information, including perfusion, uptake and kinetics. We introduced a dynamic ^{13}C 3D MRSI method that combined multiband excitation pulses with a compressed sensing (CS) acquisition and reconstruction scheme [1]. In this project, we have reduced the minimum temporal resolution by a factor of three with improved sampling and reconstruction strategies.

Methods: Two key improvements were developed for finer temporal reconstruction: (1) increased randomness in the sampling, (2) enforcing data consistency in the reconstruction. Random phase encode blips in x and y were applied during a flyback EPSI readout gradient [2], resulting in undersampling and an incoherent aliasing pattern suitable for CS. The central region in k_x-k_y was randomly sampled for each image while only selected regions in outer k-space were sampled (Fig. 1). This resulted in more temporal incoherency than our previous strategy, which fully sampled the central region without blips for each image and required 6 sec per image. Only selected outer regions - symmetric about the center of k-space – were sampled each image, reducing the number of phase encodes required while providing orthogonal spatial information in x and y.

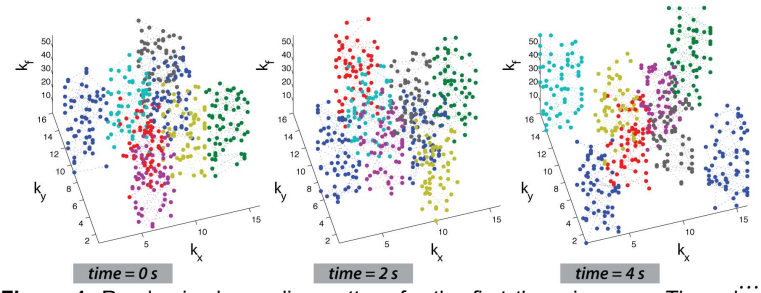


Figure 1: Randomized sampling pattern for the first three images. The color represents the phase encode ordering, which is varied for each image to increase the temporal incoherency.

The missing data was filled in iteratively using a non-linear conjugate gradient (CG) implementation [3] that takes advantage of the sparsity of the hyperpolarized ^{13}C signal. The wavelet transform applied to the time dimension was used as the sparsifying transform and a total variation (TV) penalty was also included. This sparsifying transform uses the metabolite spatial and spectral information from all time points to effectively constrain the reconstruction and exploits the generally smoothly varying temporal signal. We have added a requirement forcing strict data consistency every 20 CG iterations that also improves the reconstruction.

A spectral-spatial multiband excitation pulse was used for efficient use of the hyperpolarized magnetization [4] with a 1.75º flip angle for [1-^{13}C]-pyruvate, the injected substrate, and 12º for the metabolic products of lactate and alanine so they can be more readily observed. Animal imaging was performed on a GE 3T system using a double spin-echo sequence with TE = 160ms, TR = 250ms, 16x16x16 matrix, 5x5x5.4 mm resolution (0.135 cc) and 2 s per image.

Results: The reconstruction was validated in simulation on noisy data (SNR≤30) using 32-fold acceleration (Fig. 2). In vivo, the reconstructed spectra show substantial denoising and peak recovery when compared to zero-filling, which is very noisy because of the high acceleration factor. Using the wavelet-in-time sparsifying transform results in high quality reconstructions because it utilizes all of the temporal information. The pyruvate signal was observed to be more rapidly varying, especially in the vasculature (likely due to its high concentration in the blood), while the lactate dynamics were smoother.

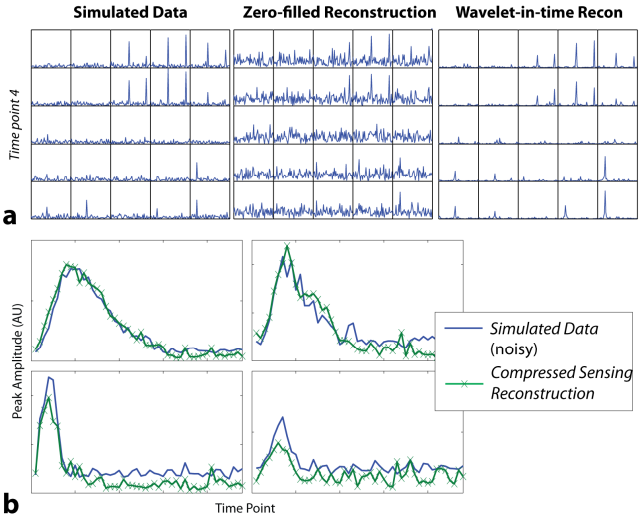
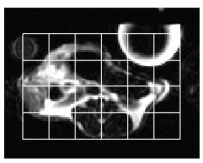


Figure 2: Simulated data reconstructions validate the new sampling and data consistency strategies.

Conclusions: The improved sampling and reconstruction strategies for compressed sensing have allowed for full 3D dynamic imaging every 2 sec – 3 times faster than our previous method.



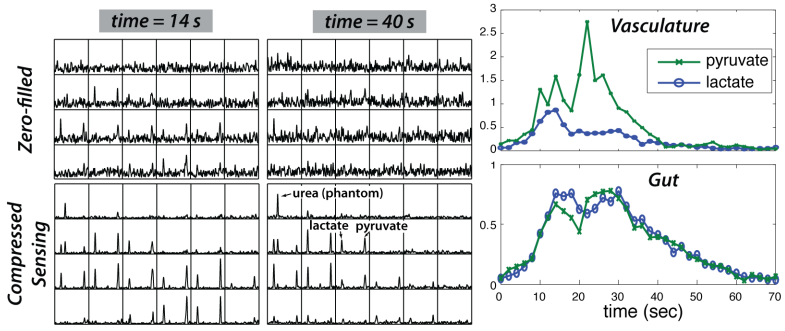


Figure 3: Normal mouse results show reconstruction quality in vivo. The pyruvate dynamics show two peaks corresponding to the initial bolus and a second bolus from clearing the catheter, which are most noticeable in the vasculature, as expected.

References: [1] Larson PEZ, et al. Proc. 17th ISMRM 2009, p. 257. [2] Hu S, et al. JMR 2008; 192: 258-264. [3] Lustig M, et al. MRM. 2008; 58: 1182–1195. [4] Larson PEZ, et al. JMR 2008; 194:121-127.

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