Fast Time-Resolved 3D Single Point Imaging with Compressed Sensing

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Introduction: Purely phase-encoded sequences such as Single Point Imaging (SPI) offer significant advantages for the study of systems with short relaxation times or large field inhomogeneities. The main drawback of such sequences is their lengthy acquisition times, making them unsuitable for rapid *in vivo* imaging, or for use in imaging dynamic systems. Compressed Sensing (CS) [1,2] has recently emerged as a way to significantly speed up the acquisition of MR images, by randomly undersampling k-space and then reconstructing the image based on data consistency and sparsity constraints. Undersampling in multiple dimensions (i.e. phase encode directions) generally increases sparsity and improves the ability of CS to reconstruct an image [2], making 3D SPI a natural candidate for CS acceleration.

In particular, we are exploring the use of CS to accelerate TurboSPI [3], a purely phase-encoded multi-spin echo sequence that can acquire several hundred time samples at each k-space location with no readout gradients. The result is a series of images with echo times differing by a few microseconds, allowing quantification of relaxation parameters across a wide dynamic range [4]. This capability makes TurboSPI well suited to R_2* mapping applications such as iron-oxide labelled cellular imaging. However, for high-resolution *in vivo* studies to be feasible, the acquisition speed of TurboSPI must be improved considerably. This work will demonstrate that CS reconstruction can be used to accelerate 3D TurboSPI acquisitions by factors of at least 6-10, without significant loss of image quality or quantitative time course information. This is achieved using a number of techniques that provide incremental improvements to the maximum undersampling factor.

Methods: All data were acquired on a 3T horizontal bore MRI system with a Varian DirectDrive console and a 305/210mm Magnex gradient coil (20 G/cm max). The RF coil was a quadrature coil with a 5cm i.d. Images were acquired of the head of a rat (*ex vivo*), and of a cylindrical phantom filled with doped water and holding NMR tubes containing different concentrations of 1.63μm diameter iron oxide particles (MPIO, Bangs Laboratories) in 4% gelatin.

For each object, a 3D FSE image was first obtained using a 128x128x16 matrix, 50x50x25mm FOV, 15mm slab excitation, TR=250ms, TE=7.5ms, ETL=8. This image took 1 minute to acquire for the phantom; for the rat, 4 signal averages were used, requiring 4 minutes. Such a "guide" image can be used to prescribe a k-space undersampling pattern with a procedure similar to that described in [5]. The magnitude of the guide image's k-space is used as a probability density function, with samples chosen at random accordingly. This reduces the number of samples required, while ensuring that important regions of k-space will be covered, and that sampling is sufficiently random to preserve incoherence under the sparsifying transform.

TurboSPI images were acquired using the same parameters as the FSE guide image, with 250 time course points sampled about the spin-echo center at 50 kHz (total time course duration 5ms). For each object, one image was acquired with a fully sampled k-space and one was acquired using the undersampling scheme prescribed by the guide image. Reconstruction of undersampled data was performed using a nonlinear conjugate gradient descent algorithm [2] with a wavelet transform used as the sparsifying transform. An additional Total Variation (TV) penalty was used for phantom data only. A low-order phase correction was applied to the undersampled data as suggested in [2], as well as to the guide image, which was supplied to the algorithm as a starting condition. Instead of processing each of the 250 3D volumes in the time course separately, the complete 4D dataset was processed as a unit to improve self-consistency. Computation of the sampling pattern and CS reconstruction were performed in Matlab using the SparseMRI library.

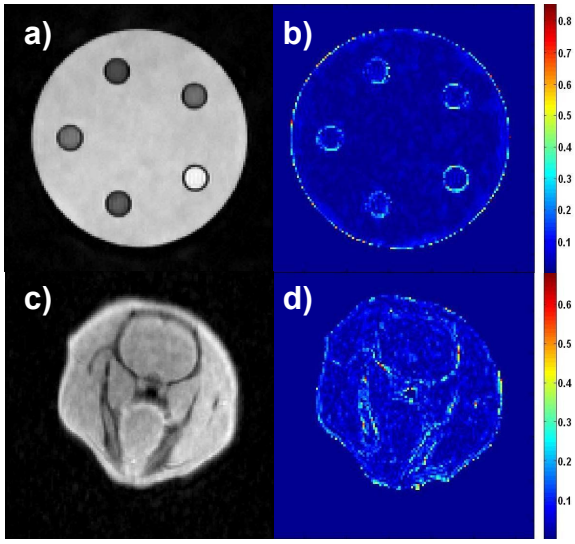

Figure 1: CS reconstruction of TurboSPI images. a) TurboSPI image of cylindrical phantom, reconstructed with CS after 10x undersampling. b) Difference between CS reconstruction and fully sampled image (mean difference = 4.13%). c) TurboSPI image of rat head, reconstructed with CS after 6x undersampling. d) Difference between CS reconstruction and fully sampled image (mean difference = 7.4%).

Results: CS reconstruction of TurboSPI images is demonstrated in Figure 1. For both objects, a fully sampled k-space (262,144 voxels) was acquired in 136 minutes. An image of the phantom was acquired with an undersampling factor of 10 (26,000 voxels) in 13.5 minutes, while an image of the rat was acquired with an undersampling factor of 6 (44,000 voxels) in 23 minutes. The mean percent difference between the CS reconstructed image and the fully sampled image was calculated over the entire 3D volume after thresholding to remove background noise. The mean difference was 4.13% and 7.4% for the phantom and rat images respectively.

The spin-echo time courses provided by TurboSPI are also unaffected by the CS reconstruction. Figure 2 shows representative time courses from two MPIO-containing tubes in the cylindrical phantom, with excellent agreement between the fully-sampled and CS reconstructed time courses. Over the entire tube, the time course information agrees to within 2.8% and 1.7% respectively.

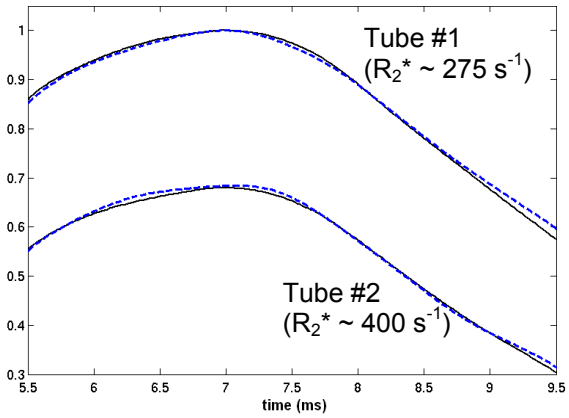

Figure 2: Representative time courses of two tubes in the TurboSPI images of the phantom (normalized to the peak signal of tube #1). The solid black lines are from CS reconstructed images, with the dotted blue lines from fully-sampled images.

Discussion and Conclusions: The increased sparsity of 3D images and the ability to undersample all 3 phase encode directions make 3D SPI well suited to CS acceleration. Acquiring a matched guide image to optimize the sampling pattern and assist the CS algorithm, as well as reconstructing the 4D dataset as a single unit, further reduces the number of samples needed for accurate reconstruction. We have shown that TurboSPI images can be accelerated by a factor of 6-10, depending on the object sparsity, with minimal loss of spatial and temporal information.

Using this methodology, 3D SPI images that typically require several hours for full k-space sampling can be acquired in times reasonable for *in vivo* imaging of animal models. For example, the modest acceleration factor of 6 demonstrated here will allow acquisition of a 300μm resolution TurboSPI scan in 1.5 hours rather than 9 hours (using a 128x128x64 matrix, 40x40x20mm FOV). Larger compression factors, potentially as high as 15-20, are anticipated for higher resolution scans with improved guide images. Such enhancements to imaging speed could be used to greatly improve the temporal resolution of dynamic imaging studies using SPI with smaller matrix sizes [5], and should greatly benefit efforts at quantitative *in vivo* cellular tracking.

References: [1] D.L. Donoho, *IEEE Trans Inf Theory* 52:4 p.1289-1306 (2006) [2] M. Lustig et.al., *MRM* 58 p.1182-1195 (2007) [3] S.D. Beyea et.al., *J. Magn. Reson.* 144 p.255–265 (2000). [4] J. Rioux et.al., *Proc. ISMRM* 17, #907 (2009) [5] P. Parasoglou et.al., *J. Magn Reson* 201:1 p.72-80 (2009)