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 CS 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 R2* 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 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, or 4 minutes to acquire for the rat. 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 according to this. This reduces the number of samples required, which in turn improves the CS reconstruction.

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The undersampling pattern 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-rank 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.

Discussion and Conclusions: The increased sparsity of 3D images and the ability to undersample all 3 phase encode directions make 3D SPI CS 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.