Compressed Sensing Reconstruction Improves Variable Density Spiral Functional MRI

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Introduction: Recent approaches to spiral imaging using variable density (VD) trajectories [1,2] have demonstrated the ability to decrease the data acquisition window for an equivalent image matrix size, with a subsequently improved fMRI sensitivity attributed to a higher time course sampling rate. In separate research, the application of Compressed Sensing (CS) reconstruction algorithms to sparse k-space data, such as VD spiral, has been shown to decrease the aliasing artifact associated with sub-Nyquist data sampling [3]. However, the use of CS reconstructed VD (CS-VD) spiral data has not been demonstrated in terms of whether its use improves sensitivity to BOLD during fMRI acquisitions, relative to conventional reconstruction methods.

In the current work we demonstrate that the use of CS-VD spiral data acquired during high field (4-T) fMRI minimizes the aliasing artifact inherent to sparse k-space acquisitions that can result in additional signal fluctuations in the time course data, thereby improving the apparent sensitivity to cortical activity relative to the same images reconstructed without CS.

Methods: All data were acquired using a 4T Varian INOVA whole body MRI system. Gradients were provided by a body coil (Tesla Engineering, UK) driven by 950 V amplifiers (PCI) with a maximum amplitude and slew rate of 35.5 mT/m and 120 T/m/s, respectively. The RF coil was a quadrature driven TEM head coil (Bioengineering Inc) driven by a 7kW RF amp (AMT). VD spiral trajectories were evaluated across a range of under-sampling values and density modification functions. Density modification was chosen such that the low frequency k-space values were acquired with approximately Nyquist sampling, with density decreasing smoothly as a function of radial distance.
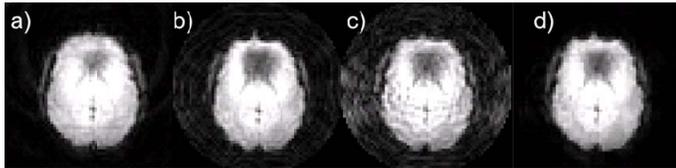
Fig 1: Comparison of (a) 2-shot uniform spiral (b) 1-shot 25 % undersampled VD spiral, (c) 1-shot 50% undersampled VD spiral and (d) 1-shot 50 % undersampled VD spiral with CS reconstruction. Note the increasing aliasing artifact as a function of undersampling for non-CS reconstructed VD acquisitions.

CS reconstruction was performed by minimizing the ℓ_1-norm of the image following wavelet transformation subject to a data matching constraint. That is,

$$\min_{x} \quad \|\Psi x\|_1 \,,$$
$$s.t. \quad \|Fx - y\|_2^2$$

where x is the image, y is the measured data, F is the Fourier transformation and Ψ is the wavelet transformation. We solve this optimization problem in its unconstrained Lagrangian form using a non-linear, conjugate gradient descent algorithm [3]. The wavelet used was the Daubechies-4 wavelet. Image reconstruction was performed on a standard, dual core desktop PC running at 2.2 GHz with 1 GB RAM. Image reconstruction took approximately 15 s per slice, or 5-10 min per volume.

Functional data was obtained using a task known to elicit activation in motor and visual cortices. Tasks were done in a block design (4 active blocks, 20 s long), and repeated for differing trajectory. All fMRI image sets (64x64) were performed with a matched volume TR of 2 s, TE of 15 ms and equivalent total slice coverage. Data sets were reconstructed both using CS, and by conventional spiral reconstruction using a Voronoi density compensation function. FMRI processing was done using the fMRI Expert Analysis Tool (FEAT) in FSL, with a cluster threshold for significance of $p = 0.01$ for all analyses.

Results: Figure 1 shows a comparison of uniform density spiral and undersampled VD spiral images. The undersampled data were reconstructed with either density compensation and re-gridding or CS reconstruction. Images reconstructed without CS show significant undersampling artifacts. This artifact increased as a function of the under-sampling, and images with even moderate sparsity showed significant degradation of image quality. Using a CS reconstruction significantly reduced these undersampling artifacts and resulted in a single shot image quality comparable to the 2-shot uniform spiral trajectory.

Figure 2 shows 4 representative axial slices from a VD fMRI data set obtained using 50% undersampling, reconstructed with and without CS. It was found that the aliasing artifact resulted in a significant decrease in fMRI sensitivity. Reconstruction using CS significantly reduced the aliasing artifact and enhanced fMRI sensitivity. At this level of sparsity, Fig. 2 clearly demonstrates the increased activation volumes across all clusters in this region, resulting from the use of CS image reconstruction. Over the entire brain, the use of CS reconstruction increased the number of active voxels (for matched z-threshold and cluster significance) by 40%.

Figure 2: Axial spiral images (64x64, TE/TR = 15/2000 ms) acquired using variable k-space density with 50% undersampling. Representative slices are shown with fMRI activity overlaid on the raw spiral images. Images in the top row were reconstructed using Compressed Sensing, while images on the bottom were reconstructed using conventional density compensation only. CS reconstructed data exhibited a 40% increase in total voxels exceeding a matched z-score threshold across the entire brain.
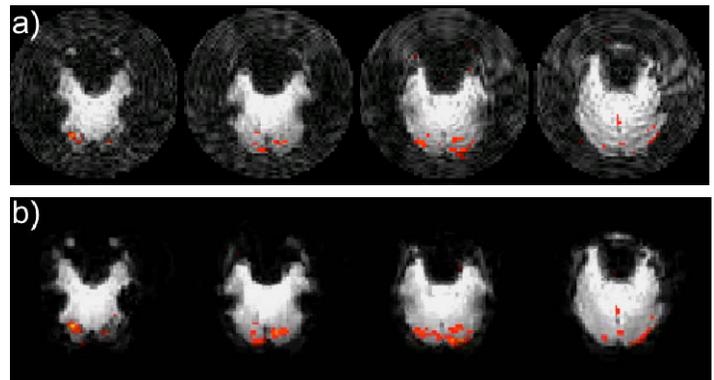
Conclusions: This work has demonstrated that fMRI data obtained using undersampled k-space through variable density spiral trajectories benefits from reconstruction using Compressed Sensing. The resulting suppression of under-sampling/aliasing artifacts translates to increased fMRI sensitivity as demonstrated by a 40% increase in whole brain activation volume, clearly demonstrating that fMRI data obtained using VD trajectories should be reconstructed using Compressed Sensing. Furthermore, the use of variable density spiral k-space trajectories and Compressed Sensing reconstruction enables 1-shot fMRI data acquisitions even in regions such as inferior/medial temporal cortex, due to the shortened readout window. Doing so permits either an increase in through-plane resolution or an increase in temporal resolution, both of which have previously been shown to further improve fMRI sensitivity.

References: [1] Chang & Glover ISMRM 2010 [2], Kim *et al*, (2003) Magn. Reson. Med. **50**, 214, [3] Lustig *et al*. (2007) Magn. Reson. Med. **58**, 1182 .