Highly Sparse Spiral fMRI Reconstructed with Compressed Sensing: Trajectory Optimization for BOLD Contrast

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Introduction: Variable Density (VD) spiral has previously been shown to improve fMRI sensitivity by increasing the sampling rate (i.e. shorter TR) [1]. However, this work utilized conventional non-uniform image reconstruction methods limiting the extent of undersampling that was achievable before aliasing artifacts dominated the image. Recent advances in Compressed Sensing (CS) reconstruction have permitted accurate reconstruction of MR images from heavily undersampled data [2]. The use of CS introduces the possibility of increased k-space sparsity without the increase in artifact, which widens the range of potential "optimal" spiral trajectories for improving fMRI sensitivity. We have explored a range of heavily undersampled variable density spiral trajectories in order to optimize the fMRI sensitivity.

Of concern when specifically optimizing for fMRI is the gain/loss of BOLD contrast-to-noise (CNR), which can be greatly affected (through partial volume effects) by any loss of spatial resolution. Insufficient sampling of high-frequency k-space data, as well as effects inherent to CS reconstruction, can potentially lead to loss of spatially sharp low-contrast features. However, the long acquisition windows inherent to uniform density spiral acquisitions can also lead to image blurring due to T_2^* weighted k-space apodization. In this work we empirically optimized these two competing effects for CS-reconstructed VD (CS-VD) spiral fMRI acquisitions. A large variety of undersampling factors and density variation functions have been acquired in human subjects, combined with variation in the reconstruction parameters for CS.

Fig. 1 Representative 128x128 axial slices. a) Uniform 1-shot spiral, b) uniform 2-shot spiral, c) CS-VD 1-shot spiral, 50% undersampling, d) CS-VD 1-shot spiral, 60% undersampling. K-space sampling has been significantly decreased without a significant change in image quality.

Methods: VD spiral trajectories were chosen such that the low frequency k-space values were acquired with approximately Nyquist sampling, with inter-ring distance increasing smoothly as a function of radial distance. CS reconstruction was performed by minimizing the ℓ_1-norm of the wavelet transform of the image. A Daubechies 4 wavelet was used. The optimization was performed using a non-linear conjugate gradient descent algorithm, as described by Lustig *et al*. [2]. The Fourier transformation was performed using the re-gridding algorithm of Fessler and Sutton [3].

Functional data was obtained using a motor-visual task on a 4T Varian INOVA whole body MRI system. Tasks were done in a block design (4 active blocks, 20 s long), and repeated for differing trajectory. FMRI processing was done using the fMRI Expert Analysis Tool (FEAT) in FSL, with a z-threshold chosen to be z > 2.3 (cluster threshold for significance of p = 0.01). All fMRI runs were performed with a matched volume TR of 2 s, TE of 15 ms and equivalent total slice coverage.

Results: In total, more than fifty VD spiral trajectories were acquired and evaluated, with undersampling ranging from 20-60%. Figu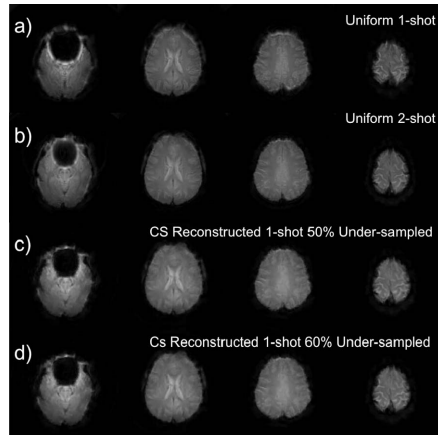re 1 shows 4 representative axial slices from spiral acquisitions acquired using conventional uniform spirals and CS-VD spirals with 50% and 60% undersampling. The increased read out time of the 1-shot uniform spiral shows a pronounced artifact particularly in regions of susceptibility induced field gradients. This artifact is reduced by using a 2-shot spiral trajectory but at the cost of either increased acquisition time, or decreased through plane resolution. CS-VD results indicate that good quality single shot images can be obtained by undersampling the k-space data. These results demonstrate that significant k-space sparsity can be introduced without impacting on image quality and contrast.

Figure 2 shows fMRI results (motor-sensory task) using a VD spiral with approximately 35% undersampling compared to a uniform acquisition with otherwise matched parameters (i.e. # of shots, matrix size, slice thickness, TR/TE). Whole brain results show a roughly 60% increase in active voxels, with a 17% increase in mean z-score. This is largely due to a significant increase in the mean percent signal change for the VD acquisition, and consequently an increase in mean CNR of 13% (calculated using all active clusters). The fMRI time course for the most significant voxel within primary motor cortex is shown in Fig. 3, which further demonstrates the improvement in BOLD CNR for the VD spiral relative to the uniform spiral. Given that the TR is the same for both acquisitions, this improvement is not due to increased time-course sampling rate.

Fig. 2 FMRI maps (p = 0.01, z-score scale 2.3-13.1) shown for a) uniform spiral & b) CS-VD spiral with 35% undersampling and matched TR, TE and slice coverage during a motor-sensory task. CS-VD spiral exhibits increased z-scores as well as activation extent.

Fig. 3 FMRI time course from highest z-score voxel within primary motor cortex for a) CS-VD Spiral (35% undersampled) and b) Uniform spiral with matched acquisition parameters.

Conclusions: The use of CS reconstructed VD spiral data for fMRI permits the use of a wider spectrum of undersampled spiral trajectories, without a significant decrease in image quality. By combining CS with VD spiral, we have demonstrated that optimal fMRI acquisitions are achieved using significantly sparser data than was previously reported for non-CS reconstructed VD spiral data. A representative CS reconstructed acquisition with 35% undersampling was shown to exhibit significantly improved fMRI sensitivity (e.g. 60% more active voxels and 13% increase in CNR). This improvement was not due to a change in the sampling rate of the hemodynamic response, but rather the difference in the k-space trajectory and corresponding decrease in the acquisition window. We hypothesize that the improvement in % signal change is due to effectively lower partial volume as a consequence of decreased T_2^* blurring during the acquisition window (i.e. an improved point spread function). Further increases in sensitivity compared to uniform spiral trajectories could potentially be obtained by combining this optimized acquisition window with an increase in the sampling rate of the hemodynamic response.

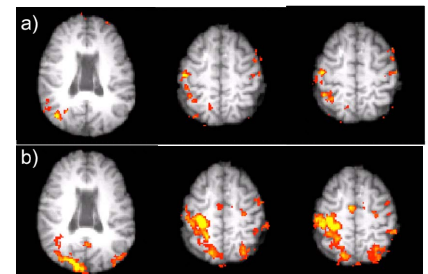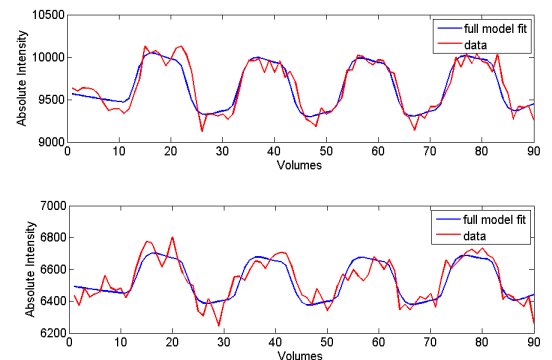**References:** [1] Chang & Glover ISMRM 2010 [2] Lustig *et al.* (2007) Magn. Reson. Med. **58**, 1182 [3] Fessler & Sutton (2003) IEEE Trans. Sig. Proc., **51**, 560.