

Compressed Sensing Improves BOLD Sensitivity at both the Individual & Group Levels

Steven D. Beyea^{1,2}, Dan Holland³, Careesa Liu¹, Xiaowei Song¹, Ryan C.N. D'Arcy^{1,4}, Tynan Stevens^{1,5}, Andy Sederman³, Lynn Gladden³, and Chris V. Bowen^{1,2}
¹Institute for Biodiagnostics (Atlantic), National Research Council Canada, Halifax, Nova Scotia, Canada, ²Physics & Radiology, Dalhousie University, Halifax, Nova Scotia, Canada, ³Department of Chemical Engineering & Biotechnology, University of Cambridge, Cambridge, United Kingdom, ⁴Neuroscience & Radiology, Dalhousie University, Halifax, Nova Scotia, Canada, ⁵Physics, Dalhousie University, Halifax, Nova Scotia, Canada

Background: In recent years, a variety of techniques have been proposed for reducing the data required to reconstruct an MR image. These techniques rely on either coherent (e.g. parallel imaging methods) or incoherent under-sampling (e.g. variable density acquisition methods). Most recently, the use of Compressed Sensing (CS) has shown promise for reconstructing images from incoherent samples that are sparse in a transform domain [1]. In CS, we utilize the fact that MRI is not innately measured in the image domain, and obtain incoherent samples by simply not acquiring all the data. Minimized data requirements shorten the sampling time, which leads to decreased blurring and resistance to off-resonance distortions [2,3]. In this work we demonstrate the ability of CS to improve fMRI data that has been under-sampled using a variable density spiral acquisition.

Methods: BOLD functional data from human volunteers (N= 15) were obtained using a block design motor-sensory task. Each 40 s block consisted of a 20 s "on" period and a 20 s "off" period, repeated 6 times for a total duration of 4 min. "On" periods consisted of simultaneous motor and visual stimulation using a paced finger-tapping task with semi-random hand alternation between blocks. During the rest periods, subjects were asked to continue fixation. Task instructions and cueing were given to subjects using visual presentation (E-Prime). Five separate runs were acquired with counter-balancing of order across subjects.

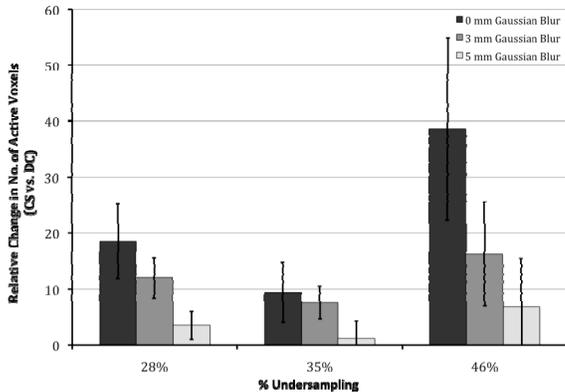


Fig. 1 Plot of the relative change in activation volume for individual fMRI data sets, as a function of reconstruction method and Gaussian filtering. Compressed Sensing increases activation volumes compared to conventional density compensated re-gridding. This effect decreases as a function of pre-statistics Gaussian filtering, with no significant difference when a very strong filter (i.e. FWHM of 2.5 times the voxel dimension) is used.

The effect of CS at the individual level can be seen in Figure 1, which shows the relative change in activation volume for the exact same data set reconstructed using CS and DC. These results show a significant improvement for data reconstructed with CS, in particular for the most highly under-sampled trajectory. However, it is interesting to note that this effect disappears when a large Gaussian blur is applied; i.e. de-noising by the Gaussian filter decreased the aliasing noise.

However, Figure 2 shows group level fMRI (28% under-sampled, shown for a slice through M1/SMA) for a Left Hand > Right Hand t-contrast, as a function of blurring level and reconstruction method. These results clearly show that a) more active voxels are detected with CS at 0 & 3-mm blurring, and b) the consequence of 5-mm blurring is to remove SMA activation. Optimal sensitivity for group fMRI occurs with a 3 mm FWHM filtering (i.e. the "standard" setting of 1.5 times the voxel dimension) of Compressed Sensing reconstructed data acquired with 28% under-sampling.

Figure 3 shows the group activation maps (3 mm FWHM) for a uniform 2-shot acquisition compared to the variable density 28% under-sampled, with both data sets reconstructed with CS and acquired with matched TR/TE. A t-contrast map ($p = 0.05$, $Z > 2.3$) between these two data sets shows no significant differences. This demonstrates that CS reconstructed variable density fMRI data can be acquired using half the number of shots, with no loss in sensitivity (which allows for significant improvements in either slice coverage or BOLD time course sampling rate).

Fig. 3 Group fMRI activation (LH > RH) for 4 representative slices, shown for Uniformly sampled 2-shot and 28% under-sampled 1-shot acquisitions (with matched TR and TE). T-contrast maps between these data sets shown no significant difference ($p = 0.05$, $Z > 2.3$).

Density modification of the variable density spiral waveform was chosen such that the low frequency k-space values were acquired with approximately Nyquist sampling, with ring spacing decreasing smoothly as a function of radial distance. Five trajectories were used: a uniformly sampled 1-shot Archimedean spiral, a uniformly sampled 2-shot Archimedean spiral, and three 1-shot variable density spirals with 28%, 35% and 46% under-sampling. The CS reconstruction algorithm that we have used is a variant of basis pursuit, which uses the ℓ_1 -norm as a surrogate for sparsity.

Data were acquired for eighteen 5-mm axial slices (128×128 matrix, $240 \text{ mm} \times 240 \text{ mm}$ field of view) with a 0.8 mm gap between slices. All acquisitions had an echo time of 15 ms and a total volume TR of 2 s. A 3D magnetization prepared fast low angle shot (MP-FLASH) anatomical with TR = 10 ms, TI = 500 ms, TE = 5 ms, 256×256 matrix, 3 mm slice thickness, and 192 mm slice phase encode were also acquired for each subject.

All work was done using a 4 T Varian INOVA whole body MRI system. Gradients were provided by a body coil (Tesla Engineering Ltd.) operating at a maximum of 35.5 mT m^{-1} at $120 \text{ T m}^{-1} \text{ s}^{-1}$, and driven by 950 V amplifiers (PCI Inc.). The RF coil used was a TEM head coil (Bioengineering Inc.) driven by a 7 kW amplifier (Herley Inc.).

Results & Discussion: fMRI data acquired using the 5 trajectories were analysed using both conventional pre- and post-gridding Density Compensation (DC) as well as CS. Each was then spatially filtered during pre-statistics processing with a FWHM Gaussian filter of either 0

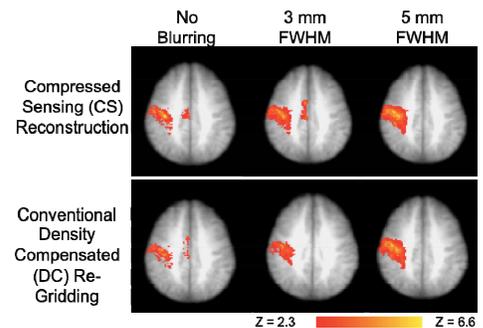


Fig. 2 Group fMRI activation (LH > RH) for a slice through M1/SMA. Images reconstructed with both conventional density compensated re-gridding and compressed sensing. Data is shown for 0 mm, 3 mm and 5 mm FWHM Gaussian filtering. fMRI cluster volume increases with CS reconstruction. A strong filter of 2.5 times the voxel size (i.e. 5 mm FWHM) results in no significant difference between CS and DC reconstructions, but does exhibit a consequent loss in SMA activation. This is due to increased blurring of the activation across the longitudinal fissure, which leads to a loss of this cluster in a LH > RH t-contrast.

Conclusions: Compressed sensing improves fMRI sensitivity at the individual and group levels, in particular for highly under-sampled data sets. Although Gaussian filtering can also provide de-noising of the aliasing artifact, CS can do so without the consequent loss of spatial resolution and impact on fMRI contrasts. Using CS, it is possible to obtain under-sampled 1-shot fMRI data with no loss in sensitivity relative to conventional uniformly sampled 2-shot acquisitions.

References: [1] Lustig M, et al., "Sparse MRI: The Application of Compressed Sensing for Rapid MR Imaging" *Magn Reson Med* 58:1182-1195 (2007). [2] Chang CE & Glover GH. "Variable Density Spiral-In/Out fMRI" *Magn Reson Med* 65:1287-96 (2011). [3] Holland D et al Proceedings of the 19th ISMRM, 2011.