Functional MRI employing Compressed Sensing and separation of signal and noise in k-space

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Introduction: The use of compressed sensing (CS)[1] in functional MRI has been limited so far[2], as it is in general more suitable for applications where the signal to noise ratio (SNR) is high. In this work, a novel fMRI analysis technique is proposed which utilizes CS to increase the frame rate while keeping the information loss in the CS reconstruction step minimal. This is achieved by applying temporal filters in k-space and partially separating the fMRI activation signal from the noise before CS reconstruction.

Methods: Starting from CS undersampled k-space data from individual receiver channels, eddy-current compensation, phase correction, temporal high pass filtering and auto regression filtering were applied. The k-space data were then decomposed into three parts: a temporal mean, an activation coefficients map, and a residual noise data series. The three parts were separately transformed to the image domain using a Total Variation regularized CS reconstruction and recombined to form an image space data series on each channel, where the reconstructed noise needed to be rescaled by a factor R_f to get an unbiased variance estimate. The final data series were produced using sum of squares summation of channel data before recalculating beta-values and variance estimates for the fMRI analysis. In order to find the rescaling factor R_f, a synthetic noise data series was generated having the same variance distribution as the data. The simulated data set was undersampled and reconstructed using CS, and the rescaling factor found by comparison of the simulated and reconstructed data. Split Bregman iterations were used for the CS reconstruction[3].

The proposed technique was evaluated on two *in vivo* CS undersampled fMRI data sets acquired on a Siemens TIM-TRIO (Siemens Healthcare, Erlangen) using the 4 CP mode channels on the 12 channel head coil. A 3D PRESTO sequence [4] was implemented using the IDEA programming tool, with segmented EPI readout and possibility for CS undersampling. FOV = 240 mm x 240 mm x 118 mm, matrix = 80 x 80 x 36 (giving 3 mm isotropic resolution), $\alpha = 10°$, TR = 22 ms, effective TE = 33 ms and echo-train length=20. One third of the total 4x36 = 144 segments were randomly selected and acquired, giving a volume time of 1.056 seconds. One block of the functional paradigm consisted of 15 seconds of rest followed by 15 seconds of visual stimulation using a flashing checkerboard with frequency of 8 Hz. The total scan time was 258 seconds or 244 frames.

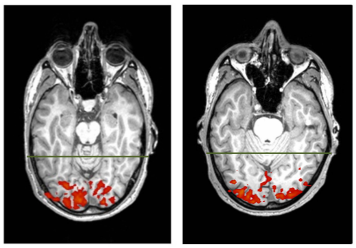

Figure 1: Axial slices of reconstructed activations maps ($P < 10^{-6}$) for subject 1 (left) and subject 2 (right).The green line separates anterior and posterior parts, see Table 1.

Table 1: Statistics from the fMRI analysis, two-sided tests are assumed when calculating P-values.

Anterior part	Subject 1	Subject 2
#Voxels	89280	89280
#Voxels with $P < 10^{-6}$	672	415
#Voxels with $P < 10^{-12}$	316	143
Highest t-value (df = 243)	35.2	18.7
Posterior part		
#Voxels	141120	141120
#Voxels with $P < 10^{-4}$	37	93
#Voxels with $P < 10^{-6}$	7	14
Highest t-value (df = 243)	5.94	7.42

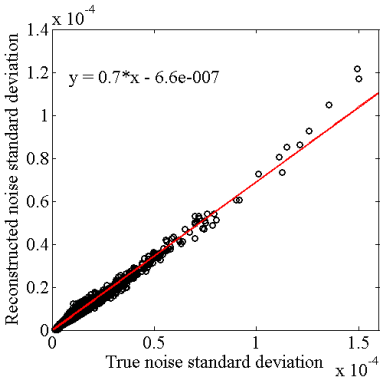

Figure 2: Simulated vs reconstructed noise.

Results: The fMRI analysis of both *in vivo* data sets correctly identified the visual cortex as the area of activation. The resulting t values were very high, and little activation was found outside the occipital region. Axial cross-sections of the reconstructed activation maps are shown in Figure 1, and some statistical data for the two measurements are presented in Table 1. The rescaling factor R_f was found to be 1/0.7 for all simulated noise distributions, an example is given in Figure 2. Reconstructed temporal mean images were decent except some signal loss in areas with rapid B0 variations, but this was not critical for the fMRI analysis as it only affected the weighting between the channels in the final reconstruction.

Discussion and Conclusion: The results show that by using the proposed method, the degradation of image quality due to CS reconstruction is outweighed by the increased number of frames and improved removal of non-thermal noise. In this case the frame rate is close to the heart frequency, meaning that much of the signal from heart beats folds down to the lower frequency region where it is removed by the initial highpass filter. Motion correction was not performed, but reconstruction of the data frame by frame is possible with quality that makes motion correction feasible. Further work will address the signal loss in areas of the reconstructed mean images, and include simulations to evaluate the robustness of the method as well as its applicability for areas with weaker activation signals.

References: [1] Lustig et al. MRM 58(6), pp 1185-1992, 2007. [2] Jung et al., Biomedical Imaging: From Nano to Macro, ISBI'09. IEEE International Symposium on, pp 702-705, 2009. [3] Goldstein et al., SIAM Journal of Imaging Sciences 2(2), pp 323-343, 2009. [4] Liu et al. MRM 30(6), pp. 764–768, 1993.