Characterization and Suppression of System Noise Due to Scanner Instability in fMRI using a SMART PHANTOM BOLD Simulator

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Introduction: In blood oxygenation level-dependent (BOLD) based functional MRI (fMRI), scanner instability is an important noise source that reduces the contrast-to-noise ratio (CNR) and affects the determination of hemodynamic response function (HRF). Even though this was realized early [1-3], the system noise due to scanner instability has not yet been experimentally studied and it is unknown how this would affect the HRF deconvolution. This work addresses this issue and aims to answer three questions: 1). Can we experimentally characterize the system noise due to scanner instability? 2). Is this system noise white or within a particular frequency band? 3). Can we remove this noise in HRF deconvolution? A SMART PHANTOM® BOLD simulator (Invivo Corporation, Gainsville, FL 32608) was employed in this study, and an event-related experiment was designed on a SIEMENS Allegra 3T system. High frequency noise induced by this imaging system was found in fMRI experiments on human subjects and removed based on the calibration using the BOLD simulator.

Materials and Methods: A SMART PHANTOM® BOLD simulator was developed using a standard spherical imaging phantom ($NiCl_2$*H_2O in solution of H_2O, GE, Milwaukee, WI 53201) with a Maxwell coil pair placed on opposite ends along the main magnetic field direction. The coil pair produces a small z-axis gradient in the phantom to simulate the dephasing susceptibility effects related to BOLD contrast. The gradient strength is proportional to the current flow in the coils, controlled by a computer. By changing currents concurrently during an EPI scan, scanner instability can be investigated in the sense of CNR without interference from physiological noise. Assuming scanner instability can be modeled as a system transfer function, T_{system}, an EPI scan of the BOLD simulator can be described as:

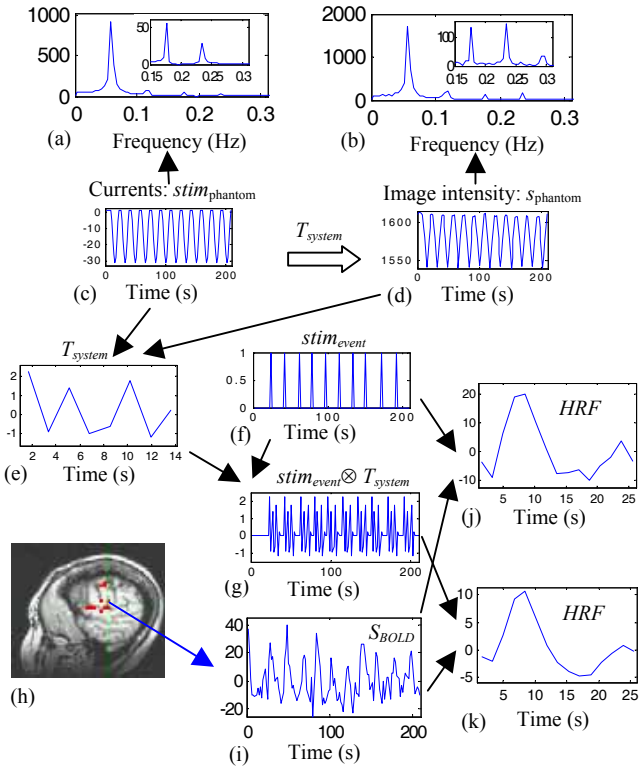
$$s_{phantom} = stim_{phantom} \otimes T_{system} \quad (1)$$

where $s_{phantom}$ is the time course signal of a series of phantom images and $stim_{phantom}$ is the driving currents in the BOLD simulator during the EPI scan. The system transfer function can be deconvolved from $s_{phantom}$ knowing $stim_{phantom}$. In a fMRI experiment on human subjects, the model becomes:

$$s_{BOLD} = stim_{event} \otimes HRF \otimes T_{system} = \left(stim_{event} \otimes T_{system}\right) \otimes HRF \quad (2)$$

where s_{BOLD} is the time course signal from a single voxel, and $stim_{event}$ is the event stimulus function (such as task event vector in a experiment paradigm). Compared with the regular BOLD based fMRI model, this model introduces a new term T_{system} to account for scanner instability. If this instability does exist, the noise correlated to T_{system} should be found in HRF deconvolution using the regular model. And this noise should be removed if the deconvolution based on equation (2) is used. To prove the theory, a slow event-related fMRI experiment was performed. Eight human subjects were asked to repeat non-words aloud and scanned using a gradient echo EPI protocol on a SIEMENS Allegra 3T system (FOV=240mm, matrix 64x64, TE=25ms, TR=1700ms, FA=70°). Each 3min run contained 123 whole brain images. There were 5 runs with 10 non-words per run, counterbalanced across the runs for phonotactic probability. Once before and once after the human scans, the BOLD simulator was scanned using the same EPI protocol. Driving currents were modulated in triangle-like waves, to approximate BOLD signal, on the same time course as the event stimulus function for human subjects. Data were processed in Matlab using least square error HRF deconvolution, and F-test to determine significance of the correlation between each voxel's signal intensity time course and the event stimulus function.

Results: The right figures show an example of data processing results. Figure (a)-(d) show the data from a scan of the BOLD simulator. Figure (c) gives the currents in the BOLD simulator and (d) gives the image intensity change. The current values are negative because the increase of currents corresponds to the decrease of image intensity. Figure (a) and (b) give the Fourier Transforms of this two time-course signal with zero-frequency components removed. The two small figures inside the large figures show the enlarged side lobes between 0.15Hz and 0.3Hz. It is clear to see that the high frequency components are enhanced more than the low frequency components, which implies the imaging system has a high frequency response. The deconvolution based on this scan gives the system transfer function, as shown in Figure (e). This gives the temporal pattern of scanner instability. Figure (h) is an anatomical brain image of a subject with active functional regions marked by red color. Figure (i) shows the time course of a voxel in the sensorimotor cortex with a correlation coefficient equal to 0.71 (F-test). The deconvolution using the corresponding event stimulus function in Figure (f) gives the HRF of this voxel in Figure (j). It can be seen that some rings of the similar pattern as in Figure (e) occurred. Based on equation (2), the event stimulus function can be first convolved with the system transfer function and the convolution result, shown in Figure (g), can then be used in the deconvolution for the same voxel. This gives the HRF in Figure (k), which shows the high frequency rings are totally removed. This processing was implemented across different subjects and voxels. The results show high correlation between the system transfer function determined using the BOLD simulator and the high frequency noise in HRF deconvolution.



Discussion: In slow event-related fMRI experiments, there are two factors that affect the level of the system noise correlated to scanner instability in HRF deconvolution. One is the length of fMRI time-course, which determines how much BOLD signal is leaked out of the primary low-frequency band. The other is the temporal sampling rate of fMRI, which determines the degree of aliasing. Practically in fMRI, the length of time-course data is limited by the tolerance of a human subject and the temporal sampling rate is limited by the speed of EPI. Because scanner instability acts as a high frequency response, the signal leaked into the high frequency band will be enhanced and fold back into the low frequency band due to aliasing. This system noise in HRF deconvolution will not be totally removed using a simple low-pass filter because of nonlinearity of aliasing. The method developed in this study will be very useful in the improvement of the accuracy of HRF determination, especially in terms of the temporal behavior, which is critical to the understanding of many important physiological processes.

Conclusions: This work has presented a technique to study the system noise due to scanner instability in BOLD-based fMRI. It was found that there exists high frequency noise correlated to scanner instability on a SIEMENS Allegra 3T system. This noise can affect HRF deconvolution due to aliasing and can be removed based on the calibration using the SMART PHANTOM® BOLD simulator. Accuracy of HRF deconvolution from human imaging data can be improved using this technique. It should also be noted that system transfer function determined using this BOLD simulator could be particular useful for cross-platform or multi-site studies.

Reference: 1). E. Yacoub, et. al., NeuroImage, 24(2005) 738-570. 2). C. Triantafyllou, et. al., NeuroImage, 26(2005) 243-250. 3). G. Wu, MRM 53(2005) 1045-1054.

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