A simple BOLD contrast model based on functional activation pattern and k-space trajectory

Vimal Singh[1] and David Ress[2]

[1]*Electrical Engineering, University of Texas at Austin, Austin, Texas, United States,* [2]*Neuroscience, Baylor College of Medicine, Hosuton, Texas, United States*

Introduction. High-resolution fMRI is attractive for a variety of applications. In particular, it is essential for imaging small brainstem nuclei such as superior colliculus (SC), a region with critical functions for eye movements and the orientation of attention. However, high-resolution fMRI requires long readout durations that are strongly affected by T2* signal decay. Typically, fMRI studies assume a readout duration much shorter than T2*, but this assumption is not valid for high-resolution fMRI. Here, we present a theory that accounts for the interaction of any *k*-space trajectory and echo time on BOLD contrast. The theory was tested by performing high-resolution fMRI in SC using a variety of single- and dual-echo spiral trajectories and EPI as TE was varied.

Theory. Assume a mono-exponential transverse signal decay, a specified functional activation pattern $h(x,y)$, and trajectory $\vec{k}(t)$. In *k*-space, the signal of interest from the pattern in the fMRI image $m(x,y)$ is: $S = \int M(\vec{k}) * H(\vec{k})\, dk$, where H and M are the Fourier transforms of h and m, respectively and * is the convolution operator. Neurovascular coupling modulates the signal, S, by varying the effective transverse relaxation rate, $R_2^* \rightarrow R_{20}^* - R_{21}^*$, to create a functional contrast, $\Delta S = \int (M * H) \exp(-R_{20}^* t)\, [\exp(R_{21}^* t) - 1]\, dk$. Because the perturbation is small, $R_{21}^* t \ll 1$, we can approximate $\Delta S \approx R_{21}^* \int (M * H) \exp(-R_{20}^* t)\, dk$.

Methods. Functional images were obtained on a Siemens Skyra 3T scanner using an interleaved spiral readout[1] (3-shots, 35 ms/echo), 1.2-mm isometric voxels, 8-10 quasi-axial slices, TR = 1s, and a 32-channel head coil. EPI data used the Siemens product sequence, same TR, anterior saturation band to permit FOV = 150 mm, matrix size 124, and 3× GRAPPA acceleration. Subjects (N = 2) viewed a moving-dot stimulus that alternated between left and right visual hemifields with a 24-sec period. The alternation was repeated 9.5 times. Subjects fixated while performing a task upon the stimuli. In separate sessions, high-resolution (0.7-mm) T1-weighted anatomical images were acquired, and the tissue of the brainstem was segmented. A smooth surface was then constructed at the CSF-tissue interface. FMRI data were aligned and resampled to this reference volume, then averaged over a 0.6—1.8-mm depth range corresponding to SC superficial layers where the visual response is strong.[2] To quantify the BOLD signal, for each functional run, a sinusoid at the stimulus repetition frequency was fit to the data to measure BOLD contrast.

Experiments begin with a baseline session for each subject that used standard single-echo spiral-out fMRI at TE = 40 ms to define retinotopic regions-of-interest (ROIs) with an area predicted by SC retinotopy[2]. Using the delineated ROIs and the imaging parameters above, our theory is used to predict BOLD contrast vs. TE for the following spiral trajectory variants: 1) out, 2) in, 3) in-in, 4) in-out and, 5) out-out, 6) EPI. Multiple tuning sessions with different echo times (6 runs/echo time) were acquired for each spiral variant. BOLD signal from the tuning sessions were fitted to the theoretical curves using a minimum least-squares formulation. Quality of fit was quantified using (1 - coefficient-of-variation (root-mean-square-error)) and by fraction of variance explained.

Results. Figure 1 shows the BOLD signal amplitude and the delineated SC based ROIs overlaid on a 3D segmentation of brainstem for subject S1. Figure 2 shows the theoretical BOLD contrast vs. TE curves for the sequence variants based on the ROIs of Fig. 1 and aforementioned imaging parameters. Relaxometry scans were used to measure the mono-exponential transverse relaxation time in the delineated ROIs. For subject S1, the T2* was measured as 51 ms over the shown ROIs. Figure 3 shows empirical BOLD data fitted to the theoretical curve for the dual echo out-out trajectory for subject S1 (1-CV(RMSE) = 0.86, r^2 = 0.42).

Conclusions. The proposed theory shows a satisfactory fit to the data, given the noise level for this subcortical brain region. The theory quantifies the need for different TEs to obtain best contrast for these different trajectories. It also allows comparison of peak contrast available from different trajectories. Further measurements are in progress to evaluate the theory in primary visual cortex where fMRI data is relatively much stronger than that in SC.

References: [1]Glover,G.H. *Magn Reso Med* **44**, 412-415 (1999); [2]Katyal *et. al. J Neurophysiol* **104**, 3074-83 (2010).

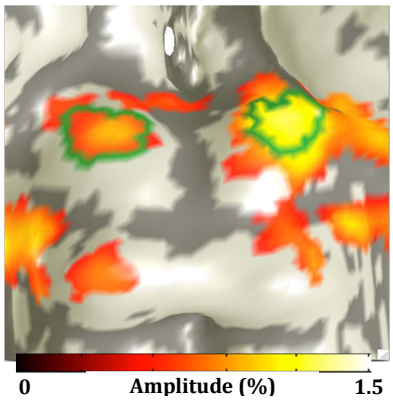

Fig. 1: Overlay of significant SC response amplitudes for a spiral out baseline session. Green lines are retinotopic ROIs.

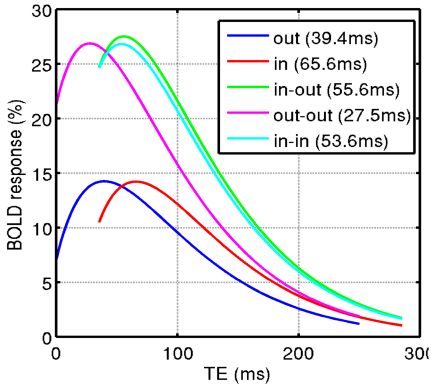

Fig. 2: Theoretical BOLD contrast versus echo time curves for various spiral variants (optimal TE in brackets).

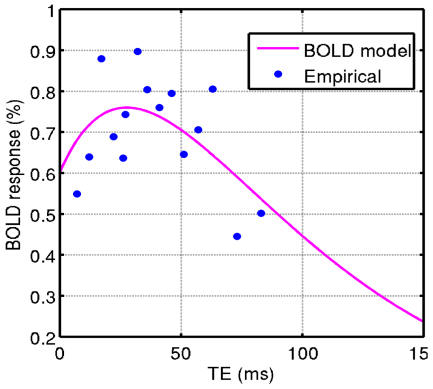

Fig. 3: Theoretical BOLD signal versus echo time curve for spiral dual echo out-out variant with empirical measured data.