Temporal Dynamics of the BOLD Impulse Response

J. A. de Zwart[1], A. C. Silva[1], P. van Gelderen[1], P. Kellman[2], M. Fukunaga[1], R. Chu[1], A. P. Koretsky[1], J. H. Duyn[1]
[1]LFMI, NINDS, National Institutes of Health, Bethesda, MD, United States, [2]LCE, NHLBI, National Institutes of Health, Bethesda, MD, United States

Introduction

BOLD fMRI allows an indirect measurement of neuronal activity. Its contrast mechanism is based on the intravascular change in deoxyhemoglobin concentration and its transit through the cerebral vasculature. This has implications for its spatial and temporal resolution which are believed to be a few mm [1] and 4-7 s [2], respectively. In this study, we hypothesized that the BOLD temporal and spatial resolution are both limited by vascular transit effects. We use a previously described model of the venous architecture [3] to simulate the impulse response function of vascular transit, and compared the results with high resolution impulse response measurements in humans.

Materials and Methods

Simulations: Simulations of temporal dispersion and latency incurred in the draining vasculature were performed in IDL (Research Systems, Inc.) in analogy with a recent paper by Turner [3]. The following assumptions were made: laminar flow of erythrocytes; 100% mixing at branching points; Murray's law ($d_1^3+d_2^3=d_3^3$) applies for vessel diameters d at branching points; distance between branch points linearly depends on vascular diameter.

BOLD fMRI: BOLD fMRI experiments were performed on normal volunteers (n=11) after informed consent. The m-sequence probe method [4] with a base-period of 1 s and a length of 255 bins was used to control the visual stimulus. Stimulus on periods (m-sequence 1's) consisted of a 7.5 Hz contrast reversing checkerboard pattern for 800 ms. For the remaining 200 ms, as well as during m-sequence 0's, a grey (matched mean luminance) disk was shown. High resolution gradient-echo EPI fMRI was performed at 3.0 T (General Electric Co.) using a 16-channel brain coil [5] (Nova Medical, Inc.) with the following parameters: rate-2 SENSE; 192×144×12 matrix; 1.2×1.2×2.0 mm^3 voxels; 1 s TR; 45 ms TE; 70º flip angle; 600 s scan time, 2 m-sequence repeats. SNR was approximately 50 in visual cortex areas.

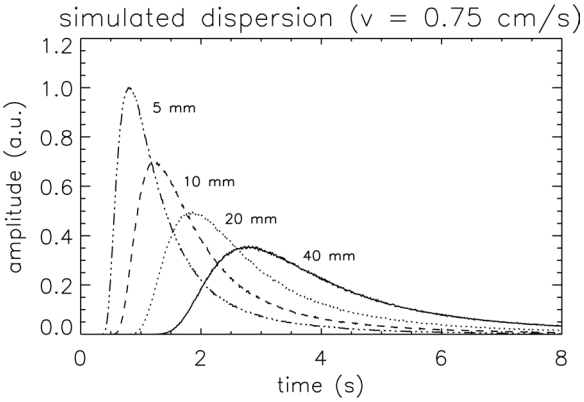

Figure 1: *Simulated dispersion in the draining vessels (0.75 cm·s^{-1} flow at 100 μm vessel diameter) at the end of 4 different flow path lengths from the capillary bed.*

Results and Discussion

Simulations: Figure 1 shows results of computer simulated dispersion during post-capillary transit. Assuming an average flow velocity of 0.75 cm·s^{-1} in the smallest veins on the cortical surface (100 μm diameter) and flow path lengths of 5-40 mm, the full-width-at-half-max (FWHM) ranged 0.9-2.5 s and time-to-peak (TTP) ranged 0.8-2.8 s.

BOLD fMRI: Measured FWHM and TTP averaged 4.03 (±0.43) and 4.52 (±0.52), respectively. A substantial dispersion, likely macrovascular in origin, was observed in the BOLD data (see example in Figures 2 and 3). Impulse responses (IR) with relatively long FWHM and TTP were observed in regions suspect of macrovascular contamination. This is demonstrated in Fig. 3, where activated voxels suspect of containing large veins (blue ×, selected based on a mask calculated from standard deviation divided by baseline intensity) are compared to all other voxels with significant activation. Averaged over this vein-weighted ROI for all volunteers, FWHM / TTP increased to 4.33 (±0.48) / 5.07 (±0.64) compared to 3.98 (±0.43) / 4.42 (±0.52) outside this ROI.

Conclusion

High-resolution BOLD fMRI shows a large spread in IR timing. Part of the dispersion (up to 2 s) is caused by transit of blood through the draining macrovasculature, which is confirmed by simulations and vein-weighted analysis of data. If macrovascular effects could be suppressed, the temporal resolution of BOLD fMRI would be improved substantially below the 4-7 s FWHM values found in literature.

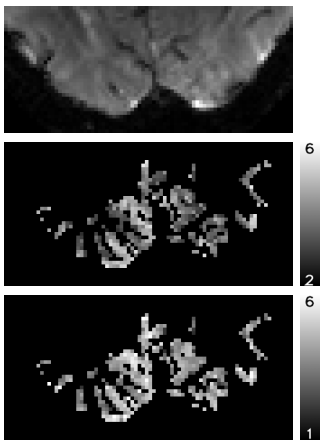

Figure 2: *Anatomy (top) and spatial distribution of TTP (center) and FWHM (bottom) values for BOLD IR (in s).*

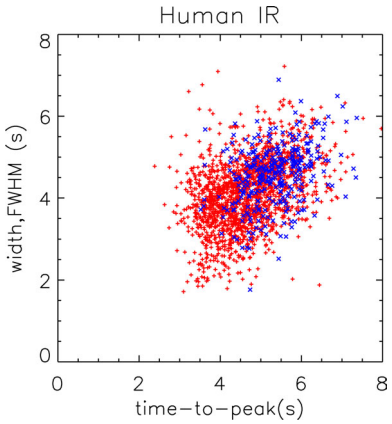

Figure 3: *Correlation between IR TTP and FWHM values for BOLD fMRI. Vein-weighted data (blue) are biased towards larger TTP and FWHM than other pixels (red).*

References

[1] Engel SA, et al. Cereb Cortex 1997; 7:181-192
[2] Aguirre GK, et al. Neuroimage 1998; 8:360-369
[3] Turner R. Neuroimage 2002; 16:1062-1067
[4] Kellman P, et al. Neuroimage 2003; 19:190-199
[5] de Zwart JA, et al. Magn Reson Med 2004 [in press]