Investigating the post-stimulus undershoot of the BOLD signal - a simultaneous fMRI and fNIRS study

Matthias L. Schroeter#, Thomas Kuppka*, Toralf Mildner*, Kâmil Uludağ§ and D. Yves von Cramon*#*

**Max-Planck-Institute for Human Cognitive and Brain Sciences, Stephanstr. 1A, Germany*
#Day Clinic of Cognitive Neurology, University of Leipzig, Liebigstr. 22A, 04103 Leipzig, Germany; §fMRI Center of the Department of Radiology, University of California San Diego, 9500 Gilman Drive/Osler Lane, La Jolla, CA 92039-0677, USA
email: schroet@cbs.mpg.de

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Introduction

The origin of the post-stimulus undershoot of the blood-oxygenation level dependent (BOLD) signal is controversial (Aubert and Costalat, 2002; Buxton et al., 1999). Three mechanisms have been discussed:

- The regional cerebral blood volume (rCBV) may return later to baseline than blood flow (rCBF) due to delayed venous compliance as proposed by the Balloon and Windkessel models.
- The undershoot may reflect the persistence of a high oxygen consumption after rCBF has returned to baseline.
- An undershoot of the rCBF could contribute to the BOLD signal undershoot.

To explore the mechanisms of the post-stimulus undershoot we measured the hemodynamic response in the visual cortex simultaneously with functional near-infrared spectroscopy (fNIRS) and functional magnetic resonance imaging (fMRI) .

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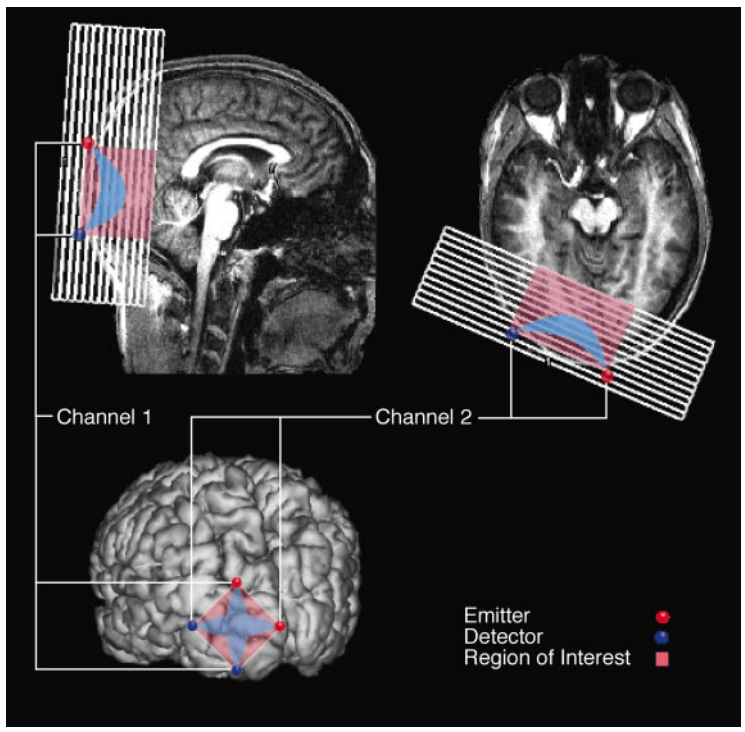

Figure 1 Sampling volume (blue) between the two emitter-detector pairs of fNIRS in relation to the slices of fMRI (white). Highest correlation between oxy-/deoxy-hemoglobin and the BOLD signal is expected for the slice in the center of the banana-shaped fNIRS sampling volume.

Materials and Methods

- 12 healthy subjects participated in the study (mean age 24.8±1 years).
- A simple visual task was employed (array of red L-shapes randomly rotating on a black background for 6 s).
- Changes in the concentration of oxy-, deoxy-hemoglobin (Hb) and the redox state of the cytochrome-c-oxidase (Cyt-Ox) were measured by a NIRO-300 spectrometer (Hamamatsu Photonics K.K., Japan).
- Two emitter-detector pairs were placed crosswise centered at position O1 of the international 10/20 system (Figure 1).
- fMRI experiments were performed using a 3.0 T whole-body scanner (3.0 T Medspec Scanner, Bruker, Germany). 12 oblique slices were oriented parallel to the plane spanned between the two emitter detector pairs.

REFERENCES:

Aubert, A., Costalat, R., 2002. A model of the coupling between brain electrical activity, metabolism, and hemodynamics: Application to the interpretation of functional neuroimaging. NeuroImage 17, 1162-1181.
Buxton, R.B., Wong, E.C., Frank, L.R., 1999. The post-stimulus undershoot of the functional MRI signal. In: Moonen, C.T.W., Bandettini, P.A. (Eds.), Functional MRI. Springer, Berlin, pp. 253-262.
Schroeter, M.L., Kupka, T., Mildner, T., Uludağ, K., von Cramon, D.Y., 2006. Investigating the post-stimulus undershoot of the BOLD signal - a simultaneous fMRI and fNIRS study. NeuroImage 30, 349-358.

Results

As illustrated in Figure 2A for one subject stimulation led to an activation in the visual cortex bilaterally around the calcarine sulcus. If the time course of deoxy-Hb as measured by fNIRS was used as a design function, the same area was activated (Figure 2B).

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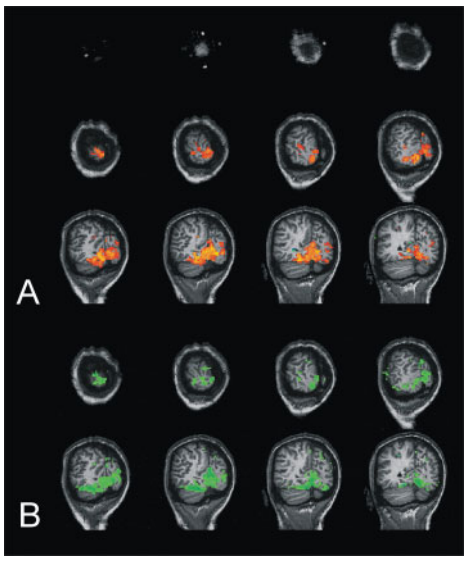

Figure 2 Averaged correlation maps for one subject. BOLD contrast. A. If a boxcar function was used as a design function ($0.85 < r < 0.95$). B. If the time course of deoxy-hemoglobin as measured by fNIRS was used as a design function ($0.8 < r < 0.83$). Optode positions are marked by vitamin E capsules (see first row in A).

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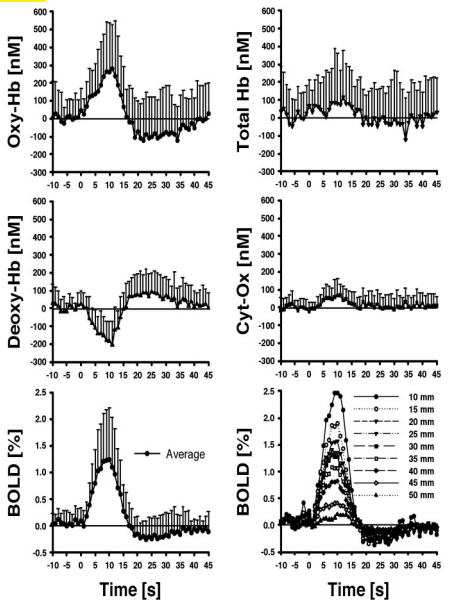

Figure 3 Concentration changes of oxy-, deoxy-, total hemoglobin (Hb), and cytochrome-c-oxidase (Cyt-Ox) as measured by fNIRS, and the BOLD signal as measured by fMRI. Visual stimulation started at 0 s and continued till 6 s. Mean±SD.

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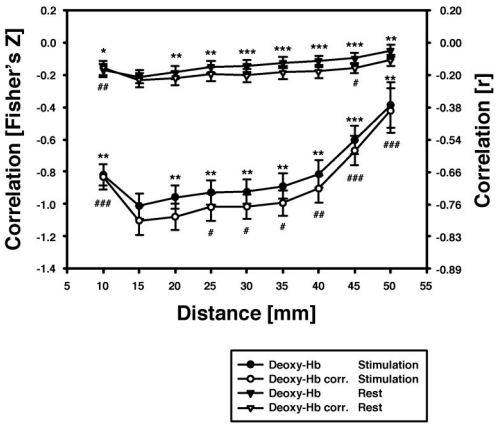

Figure 4 Depth penetration of fNIRS. Time courses of deoxy-hemoglobin (Hb) as measured by fNIRS were correlated with the BOLD signal for several distances to optode layer. Correlation is shown for visual stimulation and rest (closed eyes). Pearson correlation coefficients and partial correlation coefficients (adjusted for changes in total Hb; corr.) were normalized with a Fisher's Z transformation. Mean±SEM. *** ### p<0.001, ** ## p<0.01, * # p<0.05 2-tailed paired Student's t-test vs. values at 15 mm.

Right after stimulation onset oxy-Hb, total Hb, Cyt-Ox and the BOLD signal increased, whereas deoxy-Hb decreased (Figure 3). During the post-stimulus period, oxy-Hb and the BOLD signal decreased below, whereas deoxy-Hb increased above baseline values. Concentration of total Hb and the redox-state of the Cyt-Ox did not change. Depth penetration of fNIRS was highest for 15 mm distance from skin surface (Figure 4).

Conclusion

- Our study is the first one that investigated the post-stimulus period by both, fNIRS and fMRI.
- This multimodal approach investigates simultaneously events in the microvascular (fNIRS) and the postcapillary venous compartment (BOLD fMRI).
- Results suggest that the post-stimulus events as measured by fNIRS are dominated by a prolonged high-level oxygen consumption in the microvasculature.
- The contribution of a delayed return of rCBV to the BOLD post-stimulus undershoot in post-capillary veins as suggested by the Balloon and Windkessel models remains ambiguous.