

# Compartmental Balloon and BOLD model

K. Uludag<sup>1,2</sup>, R. B. Buxton<sup>2</sup>

<sup>1</sup>Max-Planck-Institute for biological Cybernetics, Tuebingen, Baden Württemberg, Germany, <sup>2</sup>Center for fMRI, Radiology, UCSD, La Jolla, CA, United States

## Introduction

The Blood Oxygenation Level Dependent (BOLD) effect in response to activation is sensitive to the concentration change of deoxygenated hemoglobin (deoxy-Hb), which in turn is dependent on cerebral blood flow (CBF), cerebral blood volume (CBV) and cerebral metabolic rate of oxygen (CMRO<sub>2</sub>). To relate these physiological quantities dynamically, Buxton et al. [1] proposed a 'balloon model' based on the distensibility of the venous vessels, and the long time constant for CBV to adjust is then treated as a biomechanical property of the vessels. Beside this physiological model, a physical signal model is necessary to translate deoxy-Hb into the BOLD signal [2]. Here, we propose an extension to the current model in modelling the dynamics of deoxy-Hb and CBV not only in the venous part but in different vascular compartments (arteriole, capillary and venule) and their individual intra- and extravascular contributions to the BOLD effect.

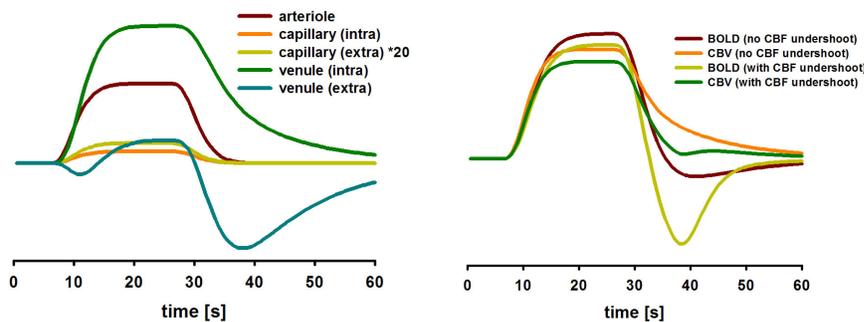
## Theory

1. *Compartmental balloon model:* The equations of the new and old balloon model represent mass conservation for blood and deoxy-Hb as they pass through different vascular compartments. We divide the vasculature into arterioles, capillaries and venules avoiding big arteries and veins. The driving inputs of the model are arterial CBF and CMRO<sub>2</sub> at the capillaries, which lead to changes in CBV and deoxy-Hb in the compartments. The outflow of one compartment is modelled as the inflow of the subsequent compartment. In addition, we treat the arterial CBV as a rigid tube and assume that the capillary CBV change is small. The change of venule CBV is calculated from the known CBF – CBV relationship for the entire CBV [3]. The transit times of each compartment are calculated from their steady-state CBV – CBF relationships.

2. *Compartmental BOLD model:* The full BOLD signal is written as volume-weighted sum of the intra- and extravascular signals of each compartment with baseline relaxation rates at 1.5T taken from the literature. The dependency of the extravascular relaxation rates at 1.5T on CBV and deoxy-Hb for venules and capillary vessels are taken from Ogawa et al. [4]. For the intravascular relaxation rates a linear relationship to oxygen saturation is used [2].

## Results

As an illustration, for a certain set of assumptions we show the contribution of the vascular compartments to the BOLD signal during activation assuming an arteriole CBF change of 50% and a CMRO<sub>2</sub> change of 25% (Figure left). Some notable features are: i) early 'dip' and post-stimulus undershoot are entirely due to extravascular venule signal, b) the biggest contribution to the BOLD signal is the intravascular venule signal being 55%, c) there is an arteriole contribution to the BOLD signal (during steady-state ~ 31%). Note that this effect is entirely due to arteriole CBV change and not to any deoxy-Hb change.



As an application of the model, we show BOLD signal and total CBV assuming no or a ~20% post-stimulus undershoot in arteriole CBF (Figure right). Without an arteriole CBF undershoot, a slow recovery of total CBV to baseline and a BOLD undershoot are observed as already predicted in the original balloon model [1]. With an arteriole CBF undershoot, the total CBV is back to baseline, while the BOLD undershoot is even more pronounced and has a different shape compared to the former case, see also [4].

## Discussion

Most of the BOLD models used are one-compartment models [1,2,5]. However, when different fMRI techniques (SE vs. GRE or CBV-, CBF- and BOLD-sensitive sequences) are used or at higher spatial resolution these models are not sufficient to explain the data. For example, as shown in the right Figure a BOLD signal undershoot can occur due to elevated venule CBV without a slow recovery of total CBV, if the arterial CBV simultaneously decreases. In a lumped model such as the original balloon model, this pattern would be interpreted as elevated CMRO<sub>2</sub> [4], rather than elevated venule CBV. Based on the new model, however, a CBF undershoot with tightly coupled CBF/CMRO<sub>2</sub> remains a possibility. In addition, the compartmental balloon model can be used to relate quantities measured with other methods: 1. The model predicts the time courses of oxy-Hb and deoxy-Hb and thus relate fMRI to NIRS data. 2. Because LDF and LSI measure all the blood moving and not only the blood delivered to the tissue, the CBF measured with these methods is different than the CBF measured with ASL fMRI or PET. The new model can incorporate / predict CBF measured with each method.

## References

[1] Buxton et al., MRM 39: 855 (1998); [2] Obata et al., NeuroImage 21: 144 (2004); [3] Grubb et al., Stroke 5: 630 (1974); [4] Ogawa et al., Biophys J. 64: 803 (1993); [4] Lu et al., JCBFM 24: 764 (2004); [5] Davis et al., PNAS 95: 1834 (1998).