

# Slab-Selective, BOLD-Corrected VASO (SS-VASO) in Human Brain at 7T

Laurentius Huber, Dimo Ivanov, Markus Streicher, and Robert Turner

Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany

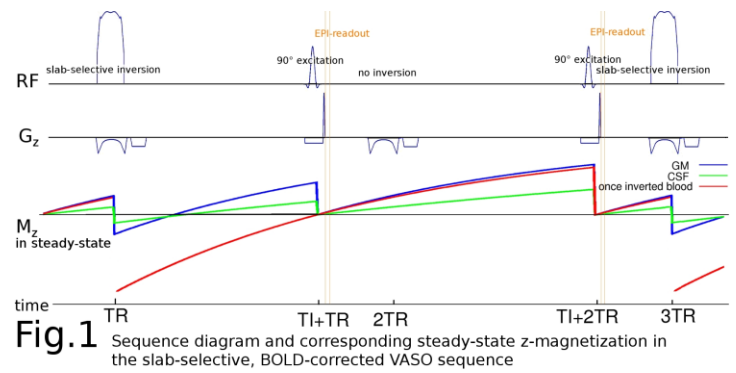
**Introduction:** Functional changes in cerebral blood volume (CBV) may localize changes in neural activity better than other MRI-accessible physiological variables [1]. Vascular space occupancy (VASO) measures CBV changes non-invasively through extravascular tissue signal change [2]. The contrast, relying on the difference in T1 between tissue and blood, is generated by applying an inversion pulse prior to acquisition that nulls blood water magnetization, while keeping substantial tissue signal for detection. At high magnetic field strengths, the remaining tissue signal at the blood nulling point is reduced, due to convergence of tissue and blood T1 values [3]. This results in a contrast-to-noise-ratio (CNR) for VASO which is disappointingly small. However, VASO CNR at the blood nulling time can be dramatically improved by applying a slab-selective gradient during inversion [4], such that proton spins in stationary tissue are in steady-state, while flowing blood is inverted only once. There are different methods to correct for the counteracting extravascular BOLD effect in VASO, e.g. small TE or multi-echo readout [5]. To assess and eliminate residual BOLD effect contamination here, we acquire BOLD data interleaved with VASO. We present results using slab-selective, BOLD-corrected VASO (SS-VASO) in human brain at 7T during a visual task.

**Methods:** The slab-selective, BOLD-corrected pulse sequence was implemented on a Siemens 7T MRI scanner. Fig. 1 shows the sequence diagram and corresponding spin magnetization. The study was approved by the local ethics committee and all subjects gave informed consent. The scan parameters were: voxel size = 1.5 mm isotropic, TE/TI/TR=19/1330/1500ms. We acquired data with 2D multi-slice single-shot GRE EPI without slice gaps. We implemented a tr-FOCI pulse [6] to achieve proper slab-selective inversion despite B<sub>1</sub> inhomogeneities and SAR constraints. A 6 min. high-contrast moving star-field paradigm (block design: 30s rest vs. 30s stimulation) was used to induce neural activation in the visual cortex of ten subjects. In four sessions, the rest period was increased to 90s, in order to investigate the signal behavior after cessation of the stimulus. To eliminate false positive voxels, a statistical analysis with a z-threshold of 2.3 and a cluster significance threshold of p=0.05 was performed (FEAT ver. 5.98) [7]. In order to ensure that all blood in the imaging slice has been inverted once and only once, we adjusted inversion slab thickness and TR with the help of pilot experiments.

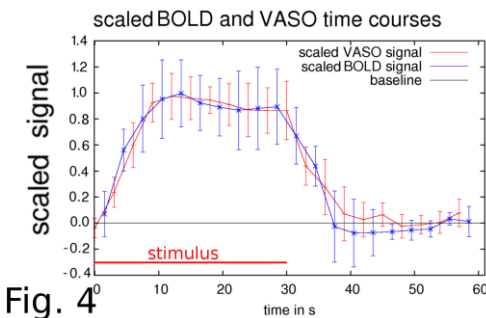
**Results and Discussion:** Slab-selective VASO provides a much larger grey matter signal than traditional VASO (Fig. 2). This increase results from the longer nulling time (TI) for once-inverted blood, compared with steady-state blood. Fig. 3 shows the  $\Delta$ CBV map for a single representative subject. Fig. 4 shows the time course of BOLD and VASO signals averaged across all ten subjects. The measured average change in CBV of 28%  $\pm$  5% is in good agreement with the literature [8]. The VASO signal change appears to vary less than BOLD across subjects, giving smaller error bars as shown. The lower inter-subject reproducibility in BOLD could be a consequence of multiple physiological factors (e.g. CBF, CBV, CMRO<sub>2</sub>) contributing to BOLD changes, including biological causes such as hormonal changes, arterial concentration of CO<sub>2</sub> and hematocrit [9,10]. Variations in attention across the subjects can be strongly mirrored in oxygenation metabolism and BOLD signal variations [11], resulting in larger inter-subject variations. Another reason for better inter-subject stability in VASO might be due to the reduced signal drift resulting from the pair-wise subtraction that corrects for BOLD contamination. The coefficient of variation (CV) [9] is 20% in VASO and 26% in BOLD. This number considers the variation of the signal change independent of the vascular response function. Since signal drifts between the 30s of activation and rest are negligible, the difference in CV is expected to be independent of signal drifts. The CV of 26% in BOLD is consistent with the literature [9,10]. We see a smaller CV in CBV compared to literature values of CV in CBF. Due to the low Grubb value of  $\alpha \approx 0.38$  [12], CBV is expected to have a lower CV than CBF. Fig. 5 depicts the spectrum of BOLD and VASO timecourses. Signal variations with wavelengths above 60s are similarly represented (black arrow). This further suggest, that the better inter-subject stability in VASO is not caused by better signal drift correction, but is caused by physiological reasons. The post-stimulus return to baseline has a similar time constant for VASO and BOLD signals, contrasting with [13] but in agreement with [14]. This result may be due to the absence of significant changes in venous CBV with short stimulus durations [15]. In voxels containing more than 10% CSF partial volume, the BOLD signal change is larger than the mean (p=0.026). By contrast, VASO signal change is significantly (p=0.0018) smaller in such voxels (Fig. 6). This is consistent with results showing that CBV change is smaller in voxels closer to the pial surface, in contrast with BOLD [1,4].

**Conclusion:** We have shown that VASO can give reliable and consistent CBV changes at 7T [4]. Here blood arrival and transit times are comparable to the blood nulling time after inversion, which is used in the slab-selective approach. Due to the high sensitivity and the high inter-subject stability, SS-VASO becomes a useful tool for high resolution functional brain mapping in humans at high fields.

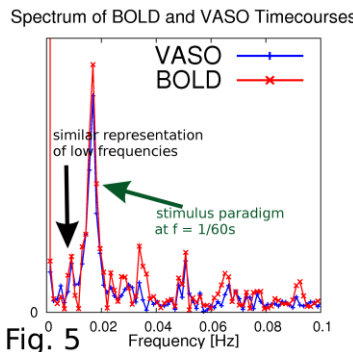
**References:** [1] Kim T, Kim SG, 2010, JSBfM [2] Lu H, et al., 2003, MRM [3] Rooney, WD, et al, 2007, MRM [4] Jin, T, et al, 2008, NeuroImage [5] Hua, J, et al., 2011, Proc. ISMRM [6] Hurley AC, et al, 2010, MRM [7] Smith SM, 2002, HBM [8] Belliveau JW, et al, 1991, Science [9] Tjandra, T, et al, 2005, NeuroImage [10] Leontiev O, et al, 2007, NeuroImage [11] Moradi F, et al, 2011, NeuroImage [12] Grubb RL, et al 1974, Stroke [13] Mandeville JB, et al, 1999, JCBFM [14] Dechent P, et al, 2010, JCBFM [15] Hillman, EMC, et al., 2007



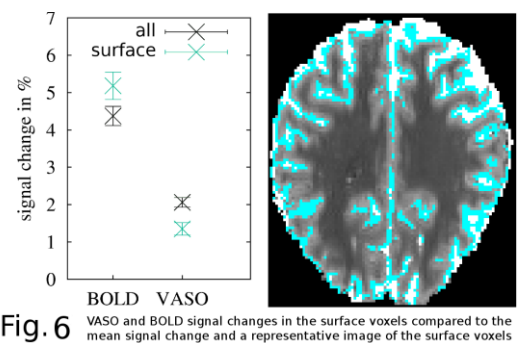
**Fig. 1** Sequence diagram and corresponding steady-state z-magnetization in the slab-selective, BOLD-corrected VASO sequence



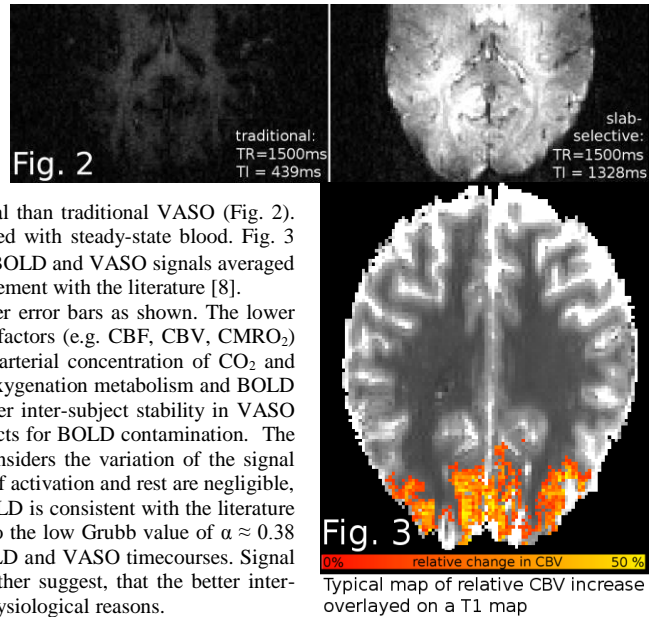
**Fig. 4**



**Fig. 5**



**Fig. 6**



**Fig. 2**

**Fig. 3** Typical map of relative CBV increase overlaid on a T1 map