Applications and Limitations of Whole-Brain MAGIC VASO Functional Imaging

A. M. Scouten[1] and R. T. Constable[1,2]

[1]Biomedical Engineering, Yale University, New Haven, CT, United States, [2]Diagnostic Radiology, Yale University, New Haven, CT, United States

Introduction

Changes in cerebral blood volume (CBV) offer valuable insight into the hemodynamic response associated with neuronal activation in the brain, and consequently the BOLD signal. CBV changes are thought to be more localized to the sites of neuronal activity than BOLD changes [1, 2] and have received recent attention for their potential in the field of human brain mapping [3]. The recently-developed non-invasive vascular space occupancy (VASO) imaging technique uses selective nulling of the blood signal to infer relative CBV changes based on a 2-compartment model in which water relocates from tissue to vasculature concomitant with activation-induced vessel dilatation [1]. A multislice extension of VASO has been proposed (Multiple Acquisitions with Global Inversion Cycling or MAGIC) and implemented with a maximum of 9 slices to measure VASO signal changes in the visual cortex [4]. Here we optimize MAGIC VASO and extend coverage to allow human whole-brain functional measurements at 3.0 Tesla. Computer simulations are developed that employ a three-compartment model incorporating both a resting and changing CSF contribution, and correction factors are obtained to account for incomplete blood nulling in particular slices. The MAGIC VASO method is tested for motor, visual, and auditory stimulation. ΔVASO/VASO maps are compared to ΔBOLD/BOLD maps for the same tasks. The relative extent of CSF contribution in different regions is discussed with supporting functional and anatomical evidence.

Methods

Theory: To fully ascertain the source(s) of the VASO signal, the potential contribution of cerebrospinal fluid (CSF) and changes in this compartment within the imaged voxel must be addressed. This necessitates the use of a 3-compartment model, containing fractions x_b, x_t, and x_c of blood-water, tissue-water, and CSF-water respectively within a voxel, where $x_b + x_t + x_c = 1$ and Δx_c is the change in CSF fraction with activation. Working from previous models [5, 6], a relationship between relative VASO signal change (ΔVASO/VASO) and relative CBV change (ΔCBV/CBV) can be derived which depends on CBV_{rest}, $x_{c,rest}$, $\Delta x_c/x_c$, and the ratios $M_b(TI)/M_t(TI)$ and $M_c(TI)/M_t(TI)$, where $M_b(TI)$, $M_t(TI)$ and $M_c(TI)$ are the longitudinal magnetizations of blood, tissue and CSF at the time of acquisition, TI. For human blood at 3.0 Tesla T_1 = 1627 ms [7], and typical CBV_{rest} and $x_{c,rest}$ of 5.5 % [2] and 0.1 [5], respectively, are used in simulations. **Figure 1** shows the relative VASO signal change as a function of resting CSF fraction ($x_{c,rest}$) and relative CSF change ($\Delta x_c/x_{c,rest}$) for a ΔCBV/CBV of 10% (cyan) and 20% (blue). The right face, shown more clearly in **b** for two values of $x_{c,rest}$, 0.01 (dotted) and 0.1 (line), demonstrates the effect of activation-induced CSF changes on ΔVASO/VASO. Note that the arrow indicates that a ~5% decrease in CSF fraction (from 0.10 to 0.095) is enough to completely eliminate the VASO signal arising from a 20% increase in CBV. Similar CSF changes have recently been reported during visual stimulation [5]. Assuming a 21-slice MAGIC VASO acquisition with 3 slices per global inversion, at least 2/3 of the slices acquired will contain some residual blood signal due to incomplete nulling. This non-zero $M_b(TI)/M_t(TI)$ ratio results in a slice-dependent overestimation of |ΔCBV/CBV| when using a simplified model with $x_{c,rest}$=0 and Δx_c=0. To correct for this overestimation, calculated ΔCBV/CBV values must be multiplied by correction factors dependent on slice number (1..21) and $T_{1tissue}$. Given the T_1s of grey matter and white matter (1331 and 832ms, respectively, from [8]), correction factors range from 0.57 to 1.0 (GM) and from 0.93 to 1.0 (WM). These factors can be implemented using image segmentation to separate GM and WM voxels.

Fig. 1 Simulations incorporating dynamic CSF contribution to VASO signal change for two values of ΔCBV

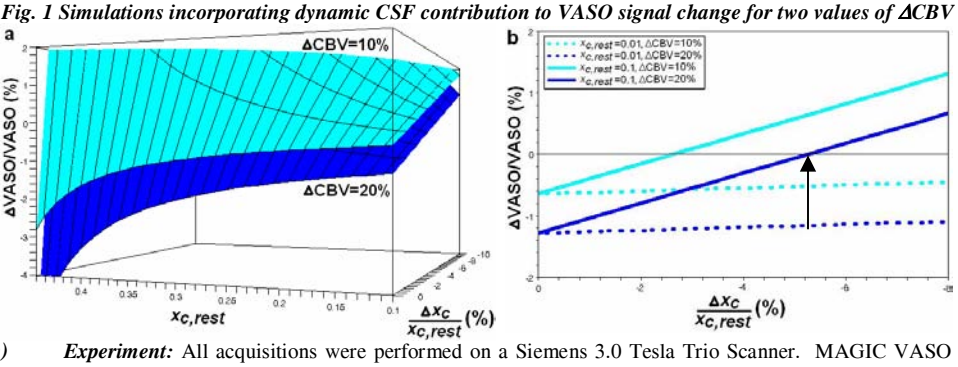
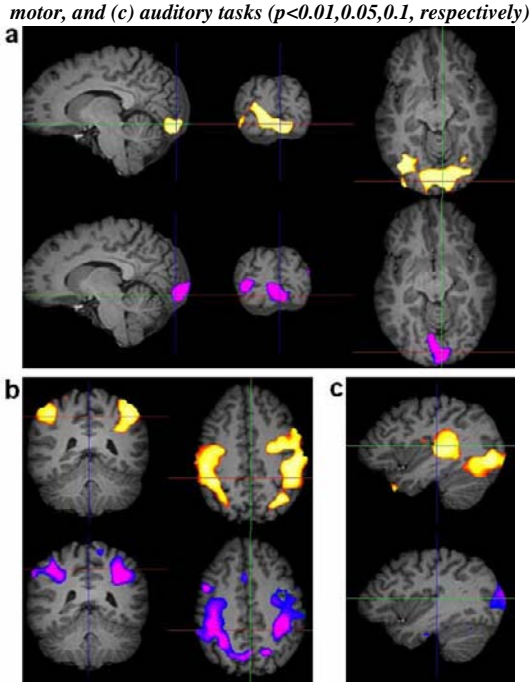


Fig. 2 BOLD & VASO t-score maps for (a) visual, (b) motor, and (c) auditory tasks (p<0.01,0.05,0.1, respectively)

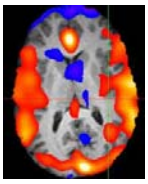


Experiment: All acquisitions were performed on a Siemens 3.0 Tesla Trio Scanner. MAGIC VASO was used with a combined motor, auditory, and visual paradigm. Acquisition parameters were: 21 axial slices (3 per global inversion) with 3.5 x 3.5 x 4 mm^3 voxels, BW = 2004 Hz/Px, TE = 8.8 ms, TR = 3000 ms. For these parameters, the TI needed to null blood was 752 ms. All MAGIC VASO acquisitions were acquired in ascending and descending slice order and averaged together for consistent signal to noise ratio (SNR) across slices. For comparison, GE-EPI BOLD images with TE = 47 ms were acquired with identical slice positioning, resolution, and TR as MAGIC VASO.

Results & Discussion

Figure 2 shows the t-score BOLD maps (top) and VASO maps (bottom) for (a) motor stimulation (N = 8), (b) visual stimulation (N = 6), and (c) auditory stimulation (N = 6). Significant negative VASO signal changes are present in both the visual and motor cortices corresponding to $\Delta CBV/CBV_{rest}$ estimates of 19±9 and 17±8%, respectively (using the simplified model with slice-dependent correction factors and region-specific values of CBV_{rest} taken from [9]). There is no detectable signal change in the auditory cortex (Fig. 2c), suggesting a contribution from changing CSF fraction to VASO. A CSF-nulled activation map in a single subject during auditory/visual stimulation (**Fig. 3**) supports this theory, with positive signal changes located in regions of higher CSF concentration, notably in the insula and the auditory cortex. This offers a compelling explanation for the lack of activation in the auditory cortex when using conventional VASO. In conclusion, without specific knowledge of the dynamic contribution of CSF, VASO imaging is severely limited in its ability to infer CBV changes.

Fig.3 Aud/vis task with CSF nulled



References:

[1] Lu, H., et al., Magn Reson Med 2003. **50**: p. 263-274. [2] Gu, H., et al., NeuroImage, 2006. **30**: p. 377-387. [3] Lu, H., et al., NeuroReport, 2005. **16**: p. 1635-1640. [4] Lu, H., et al., Magn Reson Med 2004. **51**: p. 9-15. [5] Donahue, M.J., et al., Magn Reson Med, 2006. **10.1002/mrm.21072**. [6] Lu, H., X. Golay, and P.C.M. van Zijl, NeuroImage, 2002. **17**: p. 943-955. [7] Yang, Y., H. Gu, and E.A. Stein, Magn Reson Med, 2004. **52**: p. 1407-1417. [8] Wansapura, J.P., et al., J Magn Reson Imaging, 1999. **9**: p. 531-538. [9] Giovacchini, G., et al., J Cereb Blood Flow Metab, 2002. **22**: p. 1453-1462.