A Multicompartment Vascular Model for Multimodal Analysis

T. J. Huppert[1], S. G. Diamond[2], and D. A. Boas[3]

[1]Dept of Radiology, University of Pttsburgh, Pittsburgh, PA, United States, [2]Dartmouth College, United States, [3]Massachusetts General Hospital, United States

Introduction. Stimulus evoked changes in cerebral blood flow, volume, and oxygenation arise from neuronally mediated changes in vascular tone and cerebral oxygen metabolism. However, there is increasing evidence that the magnitude and temporal characteristics of these evoked hemodynamic changes are additionally influenced by the local properties of the vasculature such as the baseline cerebral blood flow, volume, and oxygenation. In this work, we utilize a physiologically motivated vascular model that describes the dynamic characteristics of hemodynamic responses and their relationship to the structural properties of the underlying vasculature. This dynamic model allows us to perform a model-based curve-fitting of the temporal characteristics of functional MRI data to estimate the underlying cerebral vascular and metabolic properties of the brain. We present evidence of the feasibility of our model-based analysis to estimate transient changes in the cerebral metabolic rate of oxygen (CMRO2) in the human motor cortex from combined pulsed arterial spin labeling (ASL) and blood oxygen level dependent (BOLD) MRI. We examine both the numerical characteristics of this model and present experimental evidence to support this model by concurrently examining measured ASL, BOLD, and near-infrared optical spectroscopy to validate the calculated change in CMRO2 from BOLD and ASL measurements.

Methods and Theory. Our vascular model was based on three components i) a hemodynamic forward model, which depicts the underlying physiological response of the vascular network to changes in CMRO2 and the flow-inducing signal ii) a set of observation models that depict the biophysics of the BOLD, ASL, or optical imaging measurement process and iii) an inverse model, which incorporates estimates of the errors in each observation type into a weighted least-squares minimization routine. Our hemodynamic forward model is based upon the set of differential equations describing the flow and volume relationship of a compliant Windkessel chamber [1] and the oxygen transport dynamics between the vasculature and the parenchyma tissue. We used a three compartment vascular model to depict the arterial, capillary, and venous dynamics.

We collected simultaneous pulsed ASL and near-IR optical measurements from five healthy volunteers during the performance of a brief 2-second, event-related finger-tapping task. The stimulus presentation was jittered with a 500ms resolution, which allowed high-temporal (2-Hz) estimates of the hemodynamic response using a finite impulse response model. These MR and optical responses analyzed using our model. We also examined the model fits using the ASL and BOLD data alone and optical data alone. The estimated model parameters, which include characterizations of the baseline physiology and biomechanics of the vascular network, were used to estimate baseline physiological quantities for the multimodal model.

Results. Our model was used to incorporate multimodal measurements of flow, volume, and BOLD responses into a unified estimate of the underlying physiology of the vascular network. The estimates from fits to the fMRI response were consistent with our multimodal optical and fMRI estimates of CMRO2, vascular changes, and the biomechanical properties of the vasculature.

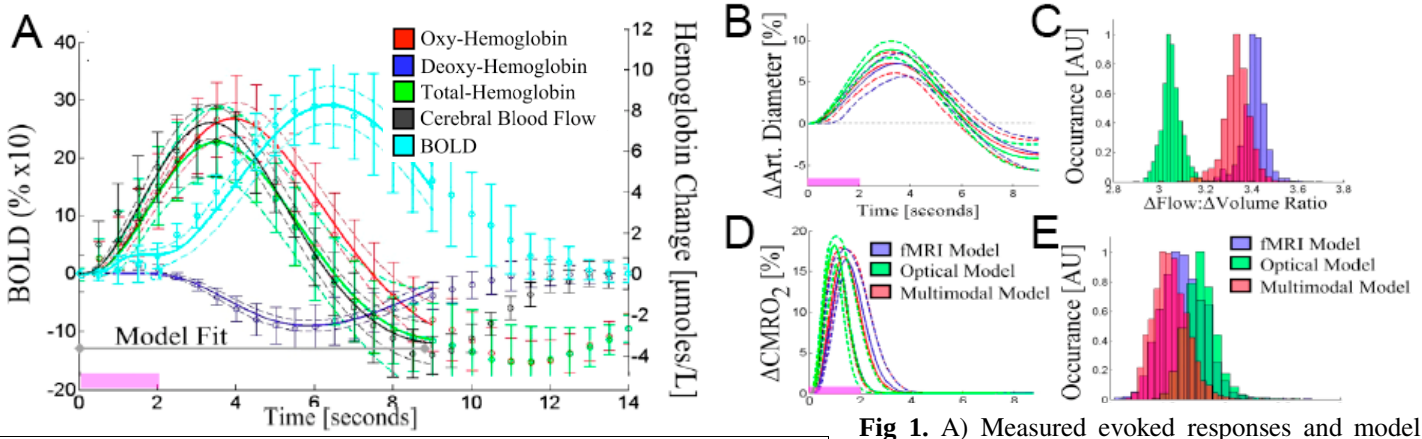

Fig 1. A) Measured evoked responses and model fits. B/D) Estimated changes in arterial dilation and CMRO2. C/E) Estimated Flow-volume and flow-consumption ratios from model fits. The model was estimated from fits to the full, fMRI only and optical only data.

Table 1. Recovered estimates of baseline physiology from the analysis of the multimodal data

Blood Volume	5.17	±	0.45	ml/100g
Blood flow	81.9	±	11.2	ml/100g/min
Hemoglobin content	12.5	±	0.3	g-Hg/dL
Oxygen delivery	14.2	±	1.9	ml O_2/100g/min
Oxygen extraction	36.6	±	0.5	%
$CMRO_2$	5.18	±	0.68	ml O_2/100g/min

[1] Mandeville, J. et al. (1998) *Magn Reson Med* 39, 615-24.