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DYNAMIC MODELLING OF LAYER SPECIFIC CORTICAL TEMPERATURE FOR QUANTITATIVE FMRI

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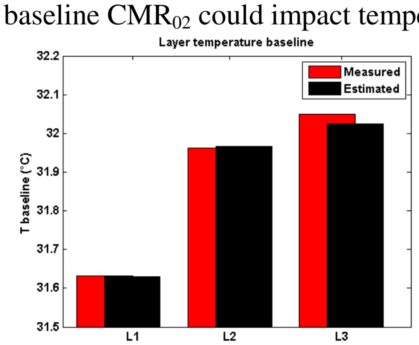
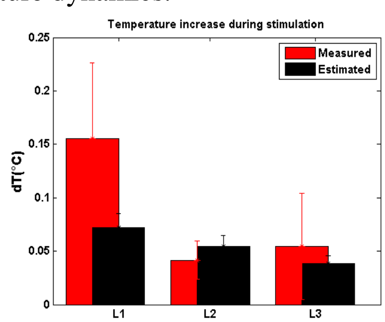
Target audience: Researchers working in Neuroscience, interested in fMRI and quantitative MRI
Purpose: Changes in BOLD signal are a consequence of different metabolic and vascular parameters including Cerebral Blood Flow (CBF), Cerebral Blood Volume (CBV) and oxygen consumption (CMR_{02}). In addition, spatiotemporal dynamics of temperature, which is another important metabolic marker for the brain, are tightly correlated with CBF and CMR02 changes in time and space that in turn depend on BOLD fMRI data. To characterize layer-specific variations of these hemodynamic and metabolic measurements for a quantitative understanding of fMRI, we measured layer-specific temperature dynamics at rest and during stimulation and fitted these multi-modal data to a mathematical model.
Methods: Mathematical modeling: We derived the generalized Pennes heat equation on the columnar direction of the brain in terms of heat metabolism in the brain. We modeled dynamic temperature changes by the heat transferred from blood flow and the heat due to the oxygen consumption [1]. Temperature solution T(x,t) was obtained by finite element method. Simulated temperature values and changes during baseline and stimulation respectively were computed for three columnar positions. Experimental settings: Multimodal measurements were acquired from Upper (L1), Middle (L2), Lower (L3) layers of the S1FL cortex of adult male rats (n=40; Sprague-Dawley; 200–300g) under α-chloralose (~40 mg/kg/hr) during forepaw stimulation (0.3ms, 2mA, 3Hz fs, lasting 30s) [2]. Quantitative changes in BOLD, CBV, and CBF data at 11.7T were acquired as previously described [2]. Temperature was measured with copper-constantan thermocouple wire [1] and with BIRDS at 11.7T [3]. Finally, changes in CMR_{O2} were calculated with calibrated fMRI [2].
Results: Measured and estimated layer-specific temperature values and changes are shown on Figures 1 and 2 for the baseline (i.e., resting) and stimulated conditions, respectively. During baseline, temperature was lower in the upper vs. the lower layers by nearly 0.5 ^oC. The simulated results agreed well with the measured results. However during stimulation we detected a significant drop in temperature (by nearly 0.1 ^oC) from the upper layer to the middle/lower layers. While the simulated results agreed well in the middle and bottom layers, there was slight discrepancy in the upper layer probably due to presence of larger pial vessels located superficially which has warmer blood entering the brain and thus would affect efficiency of heat dissipation.
Discussion: These temperature results are in line with recent laminar calibrated fMRI results [2] showing a tighter coupling between CBF and CMR_{02} upon stimulation in the middle and lower layers which leads to small temperature changes. On the contrary the cooling effect of the CBF in the deeper layers is not present in the superficial brain, probably due to the larger temperature of the CBF entering the brain [4]. Simulation showed that core blood temperature and baseline CMR_{02} could impact temperature dynamics.





Conclusion: Our model relating CBF-CMR_{02} dynamics to temperature changes across cortical layers of the cortex helps to improve the characterization of the hemodynamics and metabolic variations occurring in the brain which in turn regulates BOLD signal. MRI temperature imaging mapping combined with fMRI measurements may shed new light on the understanding of the neurovascular and neurometabolic couplings.

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