Towards a Quantitative Relationship between the BOLD Signal and Deoxyhemoglobin Measured by Near-Infrared Spectroscopy

D. Tailor, MD, PhD[1], Y. Chen, PhD[2], and R. Reddy, PhD[3]

[1]Department of Radiology, University of Pennsylvania, Philadelphia, PA, United States, [2]Department of Bioengineering, University of Maryland, College Park, MD, [3]Department of Radiology, University of Pennsylvania, Philadelphia, PA

INTRODUCTION

The blood oxygenation state of a given tissue may be detected by Magnetic Resonance Imaging (MRI) due to the paramagnetic properties of both dissolved dimolecular oxygen and deoxyhemoglobin. The deoxyhemoglobin-mediated change in brain T_2* signal is well known and is synonymous with the blood-oxygen-level-dependent (BOLD) effect, which forms the foundation for most current functional neuroimaging studies. In this study, we explore both gradient-echo and spin-echo based sensitivity of MRI to brain oxygen levels varied by changes in inspired oxygen concentration (FiO_2). We also investigate the basis of this sensitivity to oxygen by varying spin-locking and other MR parameters and by correlating these findings to near-infrared spectroscopy (NIRS) measurements of oxy and deoxyhemoglobin. The inclusion of NIRS allows for a more direct means of accomplishing the recently proposed hyperoxia based calibration of the BOLD signal (1).

METHODS

Several anesthetized rats were subjected to a variety of FiO_2 paradigms using a custom-made gas delivery system and imaged using a solenoid volume coil optimized for rat brain imaging. Rat studies were conducted on a GE-Signa 4T Clinical MRI scanner. T_2*-weighted fast gradient recalled echo (FGRE) imaging and T_2-weighted fast spin-echo (FSE) imaging were performed using appropriate parameters. Additionally, $T_{1\rho}$-weighted imaging using a previously optimized fast spin-echo (FSE) based sequence (2) was also performed. A frequency-domain multi-wavelength instrument was used to conduct NIRS on rats using previously established techniques (3). For demonstration purposes, in accordance with an IRB approved protocol, two un-anesthetized human volunteers were studied with $T_{1\rho}$-weighted imaging on a 1.5 T clinical MRI scanner for signal enhancement during 40% FiO_2 administered via standard clinical nasal cannula at normal resting respiration.

RESULTS AND DISCUSSION

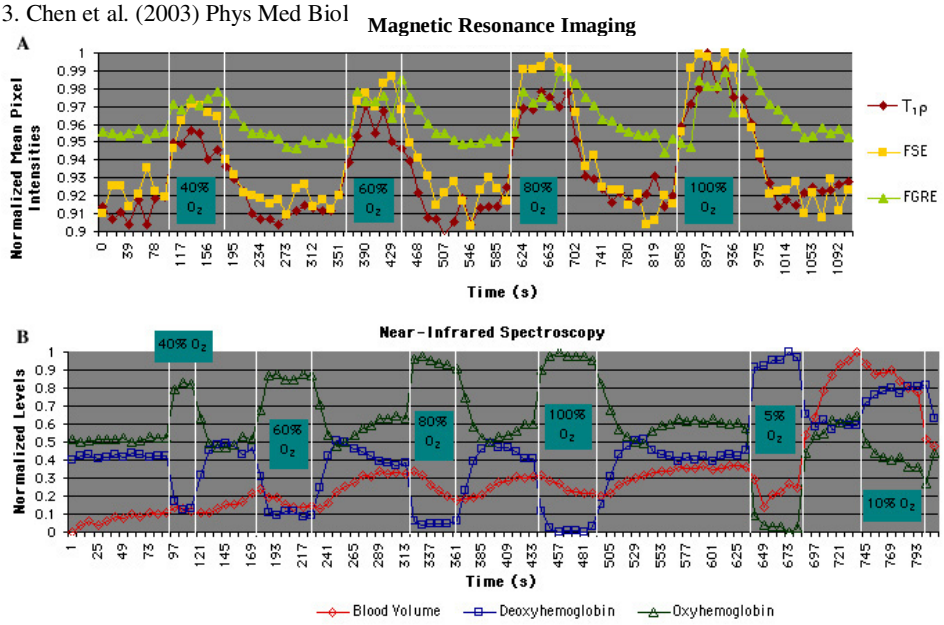
Figure 1 shows representative spin-echo and gradient-echo MRI signal changes in the rat brain (in a region of interest consisting of the bilateral frontoparietal cortex in a single coronal brain slice) and NIRS measured changes in oxy and deoxyhemoglobin (as well as estimated blood volume) due to changes in FiO_2. Figure 2 shows representative human cortical signal enhancement observed with $T_{1\rho}$-weighted MRI during inhalation of 40% oxgyen via nasal cannula.

Other results of this study (not shown in this abstract due to limited space) include the effects of varying TE and TR on the cortical signal enhancement observed with T_2-weighted FSE MRI during inhalation of 100% O_2, which demonstrate that the observed signal changes are not just determined by changes in T_1 and T_2 due to dissolved oxygen. Additionally, signal enhancement with low frequency (125 Hz) spin-locking is significantly more than that seen with high frequency (1500 Hz) spin-locking. Since the higher frequency spin-locked $T_{1\rho}$ signal is much less susceptible to deoxyhemoglobin, this data suggests that there is significant sensitivity of the spin-echo based technique for deoxyhemoglobin, a result not readily found in the literature. $T_{1\rho}$ signal decrease due to 100% CO_2 inhalation is slightly more pronounced than that for 100% N_2 inhalation. Since hypercarbia causes increased blood flow, $T_{1\rho}$ signal changes due to FiO_2 are unlikely to be blood flow dependent.

Regardless of precisely what portion of the MR signal changes are due to dissolved oxygen and what portion are directly due to deoxyhemoglobin, any combination of 1) either the spin-echo or gradient-echo signal changes, 2) the changes in oxy and deoxyhemoglobin concentrations measured by NIRS, and 3) the FiO_2 modulation pattern, yields a linearly correlated set with correlation coefficients no less than 0.95. The highly linear relationship established here between measured deoxyhemoglobin concentration and the BOLD signal corresponds to that established by indirectly estimating deoxyhemoglobin (1).

REFERENCES

1. Chiarelli et al. (2007) NeuroImage; 37: 808-20.
2. Tailor et al. (2003) Magn Reson Med; 49: 479-87.
3. Chen et al. (2003) Phys Med Biol



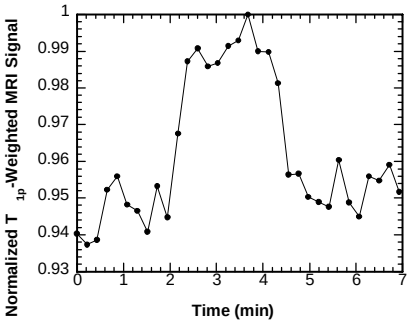


Figure 1. (Left) $T_1\rho$-weighted, FSE, an FGRE MRI and NIRS data compared. Th unlabeled regions are 20% O_2 and 80% N_2.

Figure 2. (Top) Representative human cortical signal enhancement observed with $T_{1\rho}$-weighted MRI during inhalation of 40% oxygen.