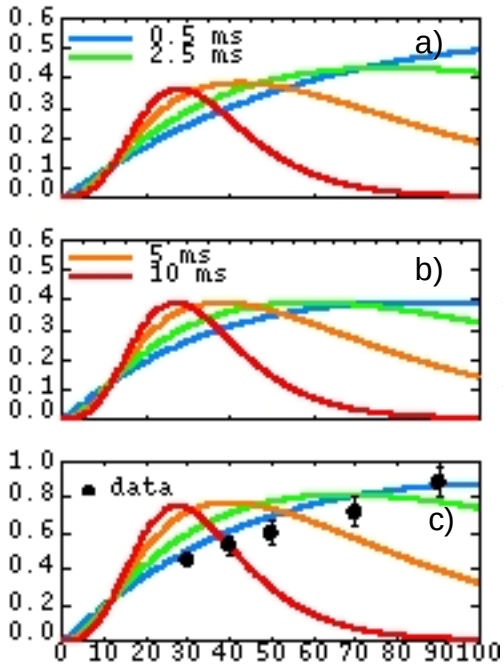
A Two Compartment Model for Spin Echo BOLD Contrast: Validation at 3 T

J. Hulvershorn[1], L. Bloy[2], E. E. Gualtieri[2], J. S. Leigh[2], M. A. Elliott[2]

[1]Biochemistry and Biophysics, University of Pennsylvania, Philadelphia, PA, United States, [2]Radiology, University of Pennsylvania, Philadelphia, PA, United States

Introduction

The Luz-Meiboom model predicts the T2 relaxation time for two-site exchange when the Larmor frequency varies between the two sites[1]. A recent paper extended the applicability of this model to include diffusion through field gradients caused by weakly magnetic particles, such as deoxyhemoglobin[2]. We modeled both the intravascular (IV) and extravascular (EV) BOLD compartments using this equation, and compared the results with those obtained from a visual fMRI experiment using multiple echo times in a spin-echo (SE) imaging series.



Materials and Methods

Ten SE EPI event related fMRI runs were performed at 3T (TR=2s; TE= 30, 40, 50, 70, 90 ms; 3.75x3.75x4 mm voxels; 14 slices), using a brief, 2s duration black and white checkerboard reversing at 8 Hz. An additional run with a diffusion gradient (b=200 s/mm^2) at TE=70 ms was conducted for one subject. SPM(T) maps were created using SPM99 and voxels exceeding a corrected height threshold (P<0.05) were selected for further analysis. Modeled T2 values for both the IV and EV compartments were generated using a modified Luz-Meiboom exchange equation[3]:

$$1/T_2 = 1/T_{20} + 24.6(1-Y)^2(B_0/1.5)^2 \times (1-\frac{2\tau_{ex}}{\tau}\tanh\frac{\tau}{2\tau_{ex}})/(1-\frac{2\tau_{ex}}{12}\tanh\frac{12}{2\tau_{ex}})$$

with T_{20}=125 ms IV, 70 ms EV; Y=0.65 rest, 0.66-0.7 active; B_0=3T; τ_{ex}=0.5, 2.5, 5,and 10 ms; and τ=TE. In this equation, τ_{ex} represents the correlation time for either diffusion or exchange between sites. The IV and EV T2 values calculated from this expression were used to obtain the expected signal contrast, assuming a blood volume (i.e. IV) fraction of 4%. T1 effects and CBV changes were ignored.

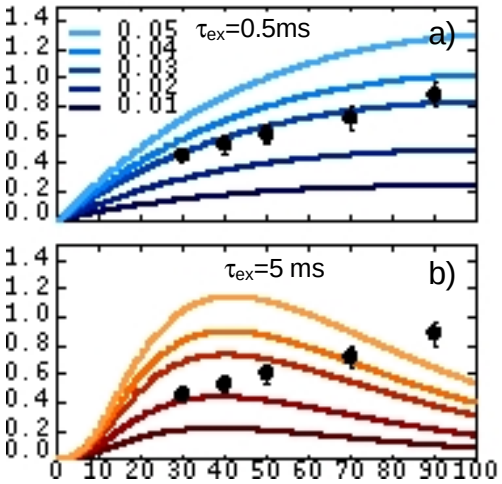
Results

Figure 1 shows the IV (a), EV (b), and total (c) BOLD contrast (in %) predicted by the model as a function of echo time for different τ_{ex}. The exchange time that best fit our experimental data was 0.5 ms, in agreement with τ_{ex} found by others in isolated blood[4,5]. Previously measured IV correlation times (τ_{ex}) for diffusion and transmembrane exchange were 0.5ms[4] and 10 ms[6], respectively. Using our multiple TE data, we calculated an apparent resting T2 of 65.8ms in the activated region of the occipital cortex. This lies within the range of 41.6 to 80 ms reported elsewhere[7]. With τ_{ex} = 0.5ms, our model predicts an apparent resting T2 of 64 ms, and ΔT2 of 0.21 ms with activation, in close agreement to the values of 65.8 ms and 0.28 ms obtained from the experimental data.

From our diffusion-weighted data, it was determined that the IV contribution to BOLD contrast was approximately 40%. This agrees with literature values of 40[8] to 50[9]%, as well as the model predicted value of 52%. **Figures 2a** and **2b** show the expected total BOLD contrast for a range of changes in hemoglobin saturation (ΔY = 0.01-0.05), with exchange times of 0.5 and 5 ms, respectively. It is apparent that at long exchange time, no value of ΔY can match the experimental data. With τ_{ex} = 0.5ms, the best fit of the data resulted in Y_{rest}=0.65 and Y_{active}=0.685.

Conclusion/Discussion

The data suggests that a diffusion-based mechanism of relaxation can describe SE BOLD contrast at 3T. We have extended the Luz-Meiboom model to describe the EV component of the BOLD contrast. The best fit of the model to our experimental data predicts an increase in hemoglobin saturation of 3.5% due to a brief visual stimulus. It should be noted that the magnitude of this change is dependent on the modeled blood volume fraction. Experimental determination of this quantity would greatly improve the confidence in these models. Similarly, the fraction of tissue that is affected by deoxyhemoglobin induced susceptibility gradients is critical. In this work, that quantity was asserted to be 0.06 (three times the capillary volume). Finally, diffusion weighted imaging at multiple TE could be used to isolate the EV BOLD component, and to validate the application of the Luz-Meboom model to that space.



References

[1]Z. Luz and S. Meiboom, Journal of Chemical Physics **39**, 366 (1963).
[2]R. A. Brooks, F. Moiny, and P. Gillis, Magn Reson Med **45**, 1014 (2001).
[3]T. Q. Duong, et al, Magn Reson Med **49**, 1019 (2003).
[4]K. R. Thulborn, et al, Biochim Biophys Acta **714**, 265 (1982).
[5]Johanna Silvennoinen, Kuopio University, 2002.
[6]T. Conlon and R. Outhred, Biochim Biophys Acta **288**, 354 (1972).
[7]J. P. Wansapura, et al, J Magn Reson Imaging **9**, 531 (1999).
[8]A. W. Song, et al, 3rd Scientific Meeting ISMRM, Nice, France, (1995).
[9]D. G. Norris, S. Zysset, T. Mildner, and C. J. Wiggins, Neuroimage **15**, 719 (2002).