A realistic vascular model for BOLD signal up to 16.4 T.

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Introduction

The blood oxygenation level-dependent (BOLD) signal using functional magnetic resonance imaging (fMRI) is currently the most popular imaging method to study brain function non-invasively. The sensitivity of the BOLD signal to different types of MRI sequences and vessel sizes is currently under investigation [1]. Gradient echo (GRE) sequences are known to be sensitive to larger vessels (venules and veins), whereas spin-echo (SE) sequences are generally more sensitive to smaller vessels (venules and capillaries), especially at high magnetic field strength [2, 3]. However, the widely used single vessel model is only an approximation to the realistic vascular distribution. Realistic vascular models have been proposed by Marques and Bowtell [4] and, recently, by Chen et al.[5]. We herein present a realistic vascular model (RVM) where diffusion is accounted for by a Monte-Carlo random walk.

Methods

The numerical Monte-Carlo process accounts for the diffusion of protons in the magnetic field of deoxygenated capillaries, venules and vessels. To obtain a realistic model, we used two-photon imaging data of blood vessels filled with a fluorescent dye (ALEXA 594) (Figure 1) located in motor cortex of an anesthetized rat. High resolution 3D image stacks were obtained that allowed all small, as well as large blood vessels to be resolved within a volume. The data has been evaluated using finite element software FEMLAB (COMSOL Multiphysics, Göttingen). The Monte-Carlo procedure has been added to the finite element model (FEM) in form of supplementary Matlab-Code (The Mathworks, Natick, MA). In the following simulations, the same susceptibility value has been assumed for all vessels. We compared the data to single vessel model data by adding the relaxation rates of single vessels with the same orientation as in the RVM.

Results

Extra-vascular relaxation rate changes induced by intra-vascular susceptibility agent, such as GdDTPA and deoxygenated hemoglobin, are similar in magnitude but not identical (cf. Figure 2 a-c and b-d) for realistic vasculature model and single-cylinder model (same vessel size distribution as in the realistic vasculature model). Especially at lower field strength, the relative discrepancy between both models is significant (cf. Fig. 3 a, b).

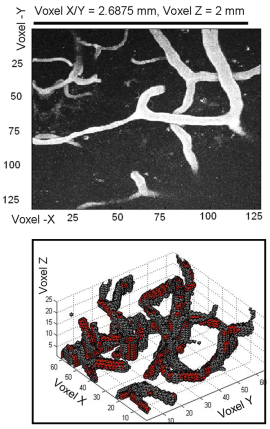

Fig. 1 (top): Image of the 2 photon imaging data (maximum intensity projection) **(bottom)**: Image of the COMSOL Setup.

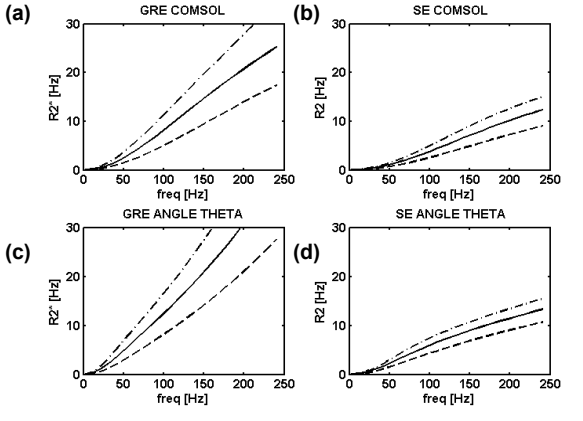

Fig. 2 (a-d): Relaxation rate for the RVM with volume fraction f = 2% (dashed line) f = 3% (solid line) and f = 4% (dashed-dotted line). GRE scenarios are shown to the left an SE scenarios to the right. On top the RVM data are shown; on bottom the single vessel data (cf. text).

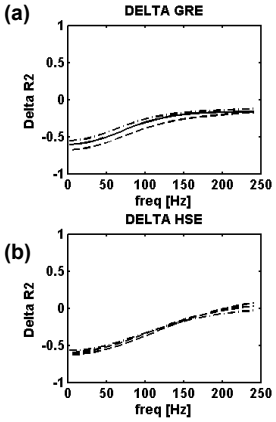

Fig. 3 (a, b): Discrepancy between COMSOL data and single vessel data.

Discussion

The MRI signal stemming from extra-vascular protons can currently not be measured but has to be evaluated using computer simulations. In this study, we performed Monte-Carlo simulations for the extra-vascular signal for field strength up to 16.4T for both GRE and SE. We used a realistic vascular model derived from two-photon imaging on rodent brain and compared the results with those obtained on single-cylinder model typically employed in such simulations. Although comparable in magnitude, relaxation rates using realistic vasculature differ from the single-cylinder model usually employed to assess the oxygenation dependence of extra-vascular BOLD signal. More simulations have to be done whether this result holds also true for other orientations of the vasculature relative to main magnetic field. Furthermore, we assumed the same susceptibility values in all blood vessels, which is correct in exogenous contrast agent experiments but not for endogenous contrast, such as deoxygenated hemoglobin, which also has to be tested.

References

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