Verification of Susceptibility Difference and Volume Fraction for the Calculation of Oxygenation Extraction Fraction using Measurements of a Single Capillary and Network Phantom

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Introduction: Quantitative estimation of cerebral tissue oxygenation extraction fraction (OEF) using MRI will provide a better understanding of the physiological state of the brain, e.g. during neuronal activation, as well as pathologies, such as tissue vitality at stroke or tumor oxygenation. The so-called quantitative BOLD imaging was demonstrated recently with very promising results [1]. However, existing phantom studies to verify the underlying theoretical approach lack an independent determination of the susceptibility difference ($\Delta\chi$) between the material used to simulate capillaries and their surrounding [2,3]. The aim of this study was to measure the $\Delta\chi$-value independently of the measurements of the capillary network. These findings were used for a proper verification of the theory.

Figure 1: Phantom setup, hollow spheres containing differently generated capillary networks, a single string is mounted vertically, i.e. perpendicular to the main magnetic field.

Material & Methods: The phantom consists of two hollow spheres (∅5cm) filled with polypropylene (PP) strings (∅100µm) immersed in a bath of silicon oil. Additionally, a single PP string (∅300µm) was mounted perpendicularly to the main magnetic field (Fig.1). Silicone oil was chosen as matrix because of its hydrophobicity. It is thus able to wet the string network completely without leaving residual air bubbles. Moreover, due to its high viscosity (approx. 100 times higher than water) diffusion can be neglected. The PP-string in one sphere was coiled randomly. The other was cut in small pieces of about 0.5 to 1.5 cm which were shuffled. Finally, in both spheres a volume fraction (λ) of about 5% was occupied by the strings. The single string was investigated by acquiring one slice perpendicular to the string axis using a gradient echo sampled spin echo - GESSE sequence (voxel size: 1x1x2mm^3). The echo timing was TE=40-195ms with ΔTE= 5ms. The spin echo was located at the 4th gradient echo with TE_{SE}=55ms. The $\Delta\chi$ value was obtained by fitting the signal decay in the voxel containing the string using a numerical simulation [4]. The capillary network was measured with a voxel size of 3x3x3mm^3 and a sequence timing of TE=80-204ms, ΔTE=4ms. The spin echo occurred at the 15th gradient echo with TE_{SE}=140ms. The data of a ROI located in the homogeneous surrounding as well as of a ROI within each sphere were fitted using the long term approximation of the static dephasing signal theory [2].

Results: A $\Delta\chi$ value of about 2.25 ppm was obtained for the single string embedded in silicon oil (Fig.2). The signal of the capillary network could be fitted very well. Furthermore, no difference was found between the two differently generated string networks (Fig.3). However, the extracted values for λ=2.54% and $\Delta\chi$=1.35ppm differ by a factor of about 0.5 from the experimentally adjusted λ and independently measured $\Delta\chi$.

Figure 2: Signal formation of a single vessel (rhombs) relative to the signal decay within a homogeneous voxel (i.e. corrected for T_2-signal decay). The fitting of the data with a numerical simulation (solid line) yields $\Delta\chi$=2.25ppm r^2=0.95, λ was fixed to 6%, the error bars denote the standard deviation of the signal in the homogeneous surrounding.

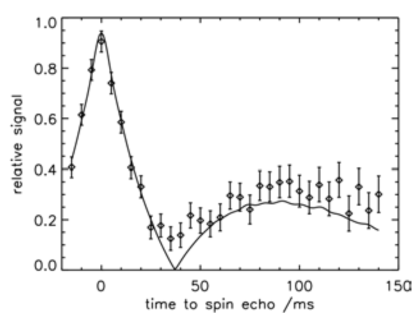
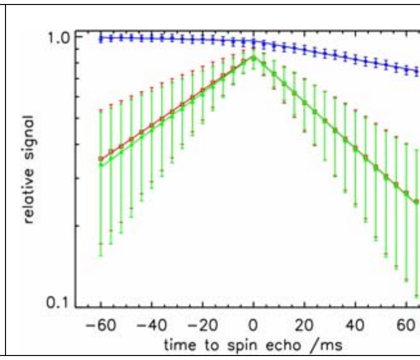


Figure 3: Signal formation of capillary networks (green, red) relative to the maximal value in the homogeneous region (blue). Fitting the data with the long term asymptotic solution yields T2=450ms, T2'=57, $\Delta\chi$=1.35ppm, λ=2.54%, r^2>0.99 for all fits. The error bars denote the standard deviation of the voxels in the according ROIs.



Discussion: The discrepancy in these findings could be explained by the relatively large $\Delta\chi$ valued caused by the chosen material. This $\Delta\chi$ is nearly 10 times higher than in normal human brain tissue [5]. Therefore, the mesoscopic field inhomogeneities induced by each strings overlap with the once of its neighbors and thus the signal theory used in this study may fail. Models of mutual avoiding cylinders [6] or spheres [7] are able to explain the effects obtained at high $\Delta\chi$ or λ values. The model of avoiding spheres was able to show that a λ of 6% will be underestimated without a correction of mutual avoiding by a factor of 2 which correlates to our findings.

Conclusion: In the near future, the mutual avoiding theory will be further investigated with respect to a more accurate description of the phantom measurements. Furthermore, the recently shown influence of different string diameters on the measured $\Delta\chi$ value [3] will be studied. Because of the independent measurement of the $\Delta\chi$ value it can be concluded that the signal theory used in this study can not be applied in this special case, in which the $\Delta\chi$ value was 10 times higher than in brain tissue.

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