Investigation of water diffusion effect on the signal relaxation in presence of a stochastic cylinder network: A phantom study

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Introduction

Quantitative mapping of oxygen supply in the brain is of great interest, providing important information about tissue viability. A static dephasing model [1] that analytically connects BOLD signal to hemodynamic parameters is commonly used to map the oxygen extraction fraction (OEF) and venous cerebral blood volume (vCBV) in the brain. This model was recently demonstrated with promising results *in vivo* [2]. However, diffusion of water molecules was not taken into consideration. The theoretical work of including water diffusion has been previously published [3], and phantom studies [4] have shown a significant influence of water diffusion for smaller capillaries. In this work, the stability of OEF measurements under non-static conditions is studied in phantom measurements.

Materials and Methods

A custom-built phantom that reflects the general qualities of the tissue model mentioned above, i.e. statistically independent cylinders with uniform and random positions and orientations in a homogeneous medium, was used for the measurements. The phantom consisted of a compartment containing randomly coiled polyamide string with a diameter of 27µm and a volume fraction of 2% in a $NiSO_4$ solution. A small string diameter was chosen in order to maximize the influence of diffusion on the signal. On a 3.0T whole body scanner (Siemens Trio, Erlangen, Germany) a gradient echo sampled spin echo sequence (GESSE) was used to acquire 32 gradient echoes with an echo spacing of 2 ms. The spin echo occurred at the 14th echo with an echo time of 63 ms. Other sequence parameters were TE_1 = 37 ms, TR = 2000 ms, BW = 1060 Hz/px, 128x88 acquisition matrix, $\Delta x = \Delta y = 2.2$ mm and $\Delta z = 10$ mm. To enhance SNR, 15 averages were acquired with a total measurement time of 44 min. T2 values of the phantom were determined in a separate measurement using a 32 echoes CPMG sequence. Additionally, the apparent diffusion constant was measured with a diffusion weighted EPI sequence. A ROI was placed in the compartment and the resulting signal curve was fitted using the static dephasing model and the water diffusion model respectively [1,3]. The susceptibility difference between the polyamide strings and the $NiSO_4$ solution was determined with the single cylinder method presented in [5] and used as reference value.

The theory of static dephasing magnetization predicts a signal decay given by (T2 relaxation is ignored in the following equation):

$$\bar{S}(t) = \rho \cdot (1-\varsigma) \cdot \exp\left[-\varsigma \cdot \bar{f}_c(\delta\omega \cdot t)\right] \quad (1)$$

where ζ is the cerebral venous blood volume fraction, and δω is the frequency shift introduced by the deoxyhemoglobin which is directly related to the susceptibility difference between the object and the surrounding medium. In case of water diffusion, the f_c-function will not only depend on the product of δω and the time, but also on an additional dimensionless parameter, λ, that depends on the diffusion coefficient and is defined as;

$$\lambda \equiv \frac{D}{R^2 \delta\omega} << 1 \quad (2)$$

where D is the apparent diffusion coefficient and R is the vessel radius. In order to study the stability of the methods mentioned above, curve fits were performed with alternating number of fit parameters (δω, ζ, and T2).

Results

The susceptibility difference between the polyamide strings and the $NiSO_4$ solution was measured, with the single cylinder method mentioned above, to a value of 1.3ppm. T2 was measured to 76 ms. The curve fitting result obtained with the two methods can be seen in figure 1 for three different parameter combinations. In figure 1a, only δω is used as a fit parameter. As can be seen in the graph, the fit obtained with the static dephasing method does not coincide with the measurement points. Even so, an acceptable value of the susceptibility difference (Δχ) is measured for both methods. In the case of two fit parameters (figure 1b and c) the static dephasing method does not manage to give a proper value of Δχ whereas the result from the water diffusion method is in agreement with the expected value. However, when using T2 as a fit parameter (figure 1c) the fit obtained with the static dephasing method coincide fairly well with the measured data point even though Δχ not at all agrees with the authentic value.

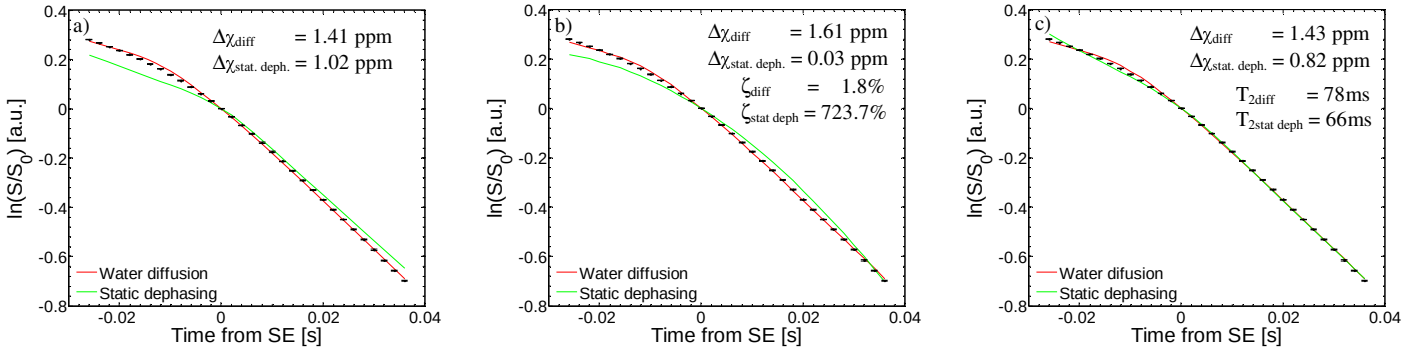

Figure 1 Measured signal curve from phantom compartment, together with the fitted signal curves for the water diffusion model and the static dephasing model respectively with a) one fit parameter (δω), b) two fit parameters(δω and ζ), and c) two fit parameters (δω and T2)

Discussion

In this work, phantom measurements were performed to determine OEF under the influence of diffusion on the signal behavior of a gradient echo sampled spin echo (GESSE) sequence. The results show that the fitting method including water diffusion yields a much better result for the susceptibility difference between strings and solution, than the static dephasing method. It should be noticed that when more than two fit parameters are used, both methods become unstable and the results will depend on the start values given to the fitting routine. This is a serious problem *in vivo* since neither the radius distribution nor the vCBV are known. Either good starting values must be used, or vCBV or the vessel radius distribution must be determined by means of another method. Furthermore, when using T2 as a fit parameter the static dephasing method can somewhat compensate for the diffusion effect seen in the measure data, but the result will be misleading. Therefore, an additional T2 measurement is recommended.

References

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