Reduction of Susceptibility-Induced Field Gradients in Anisotropic Diffusion Fibre Phantoms using Susceptibility Matching

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Target Audience: Scientists with research interest in diffusion imaging models and artificial tissue models.

Purpose: Artificial anisotropic fibre phantoms are nowadays increasingly used in the field of Diffusion Weighted Imaging (DWI) [1]. Such phantoms are perfect tools for, among others, the validation of diffusion sequences [2], theoretical models [3] and high angular resolution diffusion imaging analyses [4], since they show some important structural features of brain tissue on the one hand, but exhibit a reduced complexity, on the other. Among all used materials, Dyneema® fibres have optimal properties regarding the restriction of water diffusion and anisotropy [3]. Yet, its magnetic susceptibility is distinctly lower than that of distilled water [3]. This difference generates strong microscopic field gradients, leading to an extra T_2 weighting in those fibre populations non-parallel to the main manetic field, B_0 [3]. The presented approach aims to modify the susceptibility of the diffusing liquid to better match that of Dyneema. An aqueous solution of magnesium chloride ($MgCl_2$) is used for this purpose.

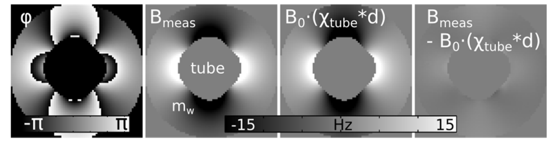

Figure 1: *Schematic example of susceptibility estimation for 50% (of maximum solubility)*

Material and Methods: The magnetic susceptibility of water is diamagnetic (about -9.05ppm [5]). The range of susceptibility in chemical compounds reaches up to high paramagnetic values, while susceptibility values lower than that of water are rare and show lower magnitude. For Dyneema, the susceptibility is approximately -10ppm [3]. Most salts are good solutes in water and many of them show diamagnetic susceptibility values. However, they show high electrical conductivity (see values in [6, p. 5-71]). For the current study, $MgCl_2$ was selected since its conductivity is lower than that of e.g. NaCl. The volume susceptibility value of pure $MgCl_2$ in SI units is $\chi = 4\pi \cdot (\rho/M) \cdot \chi_{cgs} = -19.6$ppm [7, p. 4-145, $\chi_{cgs} = -47.4$ppm], where ρ is the density and M represents the molar mass. The solubility, s, of $MgCl_2$ reaches up to 552 g/l at 20°C [7, p.8-114].

Part I: Solutions of 25%, 50% and 75% of the maximum concentration were prepared and measured at 3T in a test tube embedded in distilled water, oriented perpendicular to the magnetic field. The field distribution in the phantom is estimated using the phase data of multiple echo gradient echo sequence with standard parametrisation, manual masking with ITKSnap [8], unwrapping and background field correction with our in-house software URSULA [9] and MUBAFIRE [10]. Assuming a solid susceptibility distribution inside the tube, χ_{tube} is estimated by minimising the difference between measurement and the field generated by dipole convolution [11], $\min_{\chi_{\text{tube}}} \; ||m_{\text{w}} \cdot (B_{\text{meas}} - B_0 \cdot (\chi_{\text{tube}} * d))||_2$, evaluated in a cylindrical water mask, m_w , around the test tube (Fig. 1). A linear dependence of susceptibility and concentration with zero origin is fit to the data using Matlab (The MathWorks, Inc.).

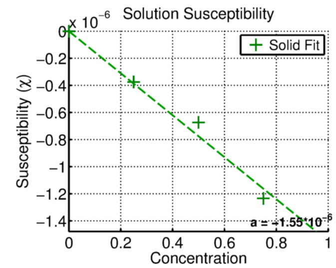

Figure 2: *Estimated susceptibility values plotted against percentage of maximum solubility*

Part II: In order to investigate the benefits of the estimated optimal solution value, s_{opt}, three fibre phantoms were prepared, using a) distilled water, b) $s_{\text{opt}}/2$ and c) s_{opt}. The tubes consist of Dyneema fibres densely packed and aligned in parallel in an approximately 2.5cm wide shrink tube [3], embedded in plastic vials that are filled with the particular liquids. All vials are assembled in a cylindrical container filled with distilled water. DWI experiments were carried out using the double-refocused spin-echo EPI sequence with bipolar DW gradients pulses. Diffusion field gradient settings were: b-values = 0, 0.2, 0.4, 0.6, 0.8, 1.0 ms/µm^2 and 20 field gradient directions. Experiments were performed for two orientations of the fibre directions with respect to B_0, i.e. $\alpha = 0°$ and 90°. Diffusion Tensor Imaging (DTI) analysis was performed using in-house Matlab scripts.

Results and discussion: *Part I:* The relation between susceptibility and concentration (in percent of the maximum solubility) is a = -1.55 ppm/100%. Expecting a relative offset of $\Delta\chi \approx -0.9$ ppm between water and the regression fit predicts an optimal concentration of $s_{\text{opt}} \approx 60\%$ (with respect to the maximum solubility). *Part II:* Fig. 3 shows the maps of the signal-to-noise ratio (SNR), mean (MD), axial (AD) and radial (RD) diffusivities for the fibres oriented along B_0 (a,b,c,d) and perpendicular to B_0 (e,f,g,h). One can observe strong artefacts in all metrics in the fibre tube with 0% $MgCl_2$ at $\alpha = 90°$ which is greatly reduced in the tubes with 30% and 60% of $MgCl_2$. Figure 4 shows the average values of all metrics taken over a region-of-interest (ROI) placed inside each tube. In these graphs one can see that the best results are achieved with the solution with 30% $MgCl_2$ (red line), in which no significant changes occur in the metrics between $\alpha = 0°$ and $\alpha = 90°$. Although optimal susceptibility matching occurs around 60% of the maximum solubility, 30% seems to be the experimental optimum. This may be caused by significant shortening of the T_2 for high concentrations, which is reflected in the SNR and drastically affects the results at 60%.

Conclusions: In this work we have shown that the effect of microscopic, susceptibility-induced field gradients on diffusion metrics in anisotropic diffusion fibre phantoms can be greatly reduced by matching the susceptibility of the liquid to that of the fibres. This brings the advantage of having a phantom where diffusion metrics are nearly independent of the fibre orientation in the external magnetic field. This is particularly important in phantoms containig multiple-fibre populations (multimodal diffusion phantoms), which have always at least one of the fibre populations non-parallel fo the static magnetic field.

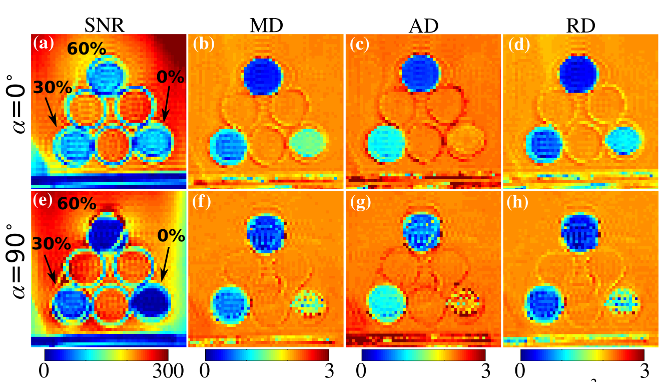

Figure 3: *Maps of SNR (a,e), MD (b,f), AD (c,g), RD (d,h) – in µm^2/ms – for fibres oriented along the main field B_0 (a,b,c,d) and perpendicular to B_0 (e,f,g,h).*

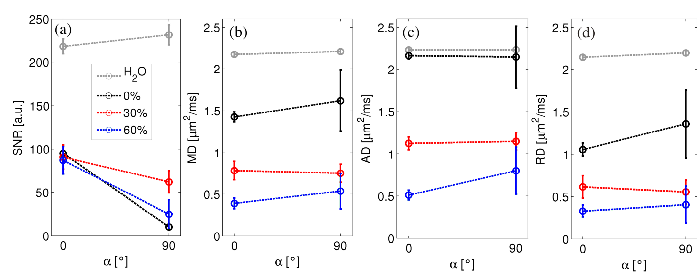

Figure 4: *Dependence of SNR (a), MD (b), AD (c) and RD (d) on α, for bulk H_2O (grey), 0% (black), 30% (red) and 60% (blue).*

References: [1] E. Farrher et al., *Magn. Reson. Imaging* 30, 518-526 (2012); [2] C. Reischauer et al., *J. Magn. Reson. Imaging* 29, 692-698 (2009); [3] E. Fieremans et al., *Phys. Med. Biol.* 53, 5405-5419 (2008); [4] C. Poupon et al., *Magn. Reson. Med.* 60, 1276-1283 (2008); [5] J. F. Schenck. *Medical Physics* 23, 815–50 (1996); [6] B. Raton, *CRC Handbook of Chemistry and Physics - Electrical Conductivity of Aqueous Solutions*. CRC Press, 70th editi ed. (1989); [7] B. Raton. *CRC Handbook of Chemistry and Physics, Internet Version 2005*. CRC Press (2005); [8] P. A. Yushkevich et al. *Neuroimage* 31, 1116–1128 (2006); [9] J. Lindemeyer et al. *Proc. Int. Soc. Mag. Reson. Med.* 21, 2494, 2013; [10] J. Lindemeyer et al. *Proc. Int. Soc. Mag. Reson. Med.* 20, 2329 (2012); [11] Koch et al., *Phys. Med. Biol.,* 51(24), 6381–402, (2006).