Novel Artificial Phantom for Studies of Anisotropic Diffusion in the Model Brain Tissue

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Introduction

Diffusion-weighted MRI is a powerful non-invasive technique to explore fibrous tissue microstructure. In particular, it finds important applications in the characterization of microstructure and physical properties of complex tissues, such as white matter in the brain. In order to establish a clear relation between theoretical models and experiments, artificial systems (phantoms) of reduced complexity are required [1,2]. In this work we present a novel diffusion phantom made of polyethylene fibres. One of the valuable features of this phantom is that it can characterise a spatial gradient of fibre density. This gives rise to a gradual change of the degree of anisotropy within the same phantom; rather high values comparable with that of white matter were achieved. In this way, the need to construct several phantoms with different fibre densities is avoided, and one can access different fractional anisotropies in the same experiment under the same physical conditions. The properties of the developed phantom are demonstrated by means of diffusion tensor imaging (DTI) and diffusion kurtosis imaging (DKI) [3].

Phantom design and results

The phantom was constructed using highly hydrophobic polyethylene fibres (Dyneema® DTX 70) of 16 μm diameter. The fibres were thickly rolled around a Perspex support (Plexiglas®), see Fig. 1a. Both sides of the phantom, Fig. 1b, exhibit a region in which fibres cross at 90º and a region in which fibres are roughly parallel. The parallel regions are designed in such a way that fibre density, f, is homogeneous on the side 1 but exhibits a spatial gradient on the side 2. This is demonstrated by the map of fibre density and the corresponding profile along the x-direction in Figs. 2a and 2b (origin indicated by the y-axis). The whole setup was immersed in a cylindrical container filled with distilled water. The phantom was placed in a vacuum pump for several hours in order to remove air bubbles.

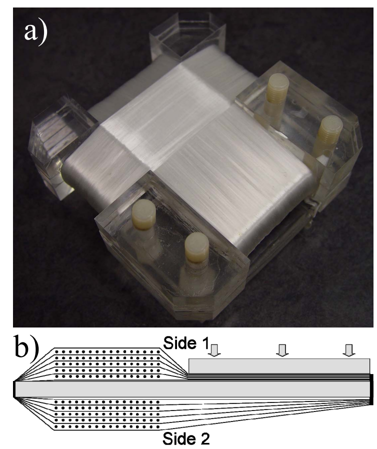

Figure 1. a) Photograph of the phantom and b) schematic side-view representation.

All measurements were performed with a whole-body 3T Siemens Magnetom Trio scanner. A spin-echo multi-contrast (SE-MC) sequence was used to estimate the fibre density, Fig. 2a. Proton density was assessed by fitting S_0 and T_2^* with the function $S(\mathrm{TE}) = \exp(-\mathrm{TE}/T_2^*)$ to the signal decay $S(\mathrm{TE})$ where TE is the echo time. The relative proton density S_r is obtained with respect to the ROI in the free water, and finally $f = 1\text{-}S_r$. Diffusion experiments were carried out with the help of a stimulated-echo (STE) diffusion echo-planar imaging pulse sequence developed in our laboratory. The duration of the diffusion pulse gradient δ was equal to 20.6 ms, and the gradient-pulse separation, Δ, was varied from 80 ms to 1000 ms. A set of 7 b-values up to 3000 s mm^{-2} were used for the 6 gradient directions.

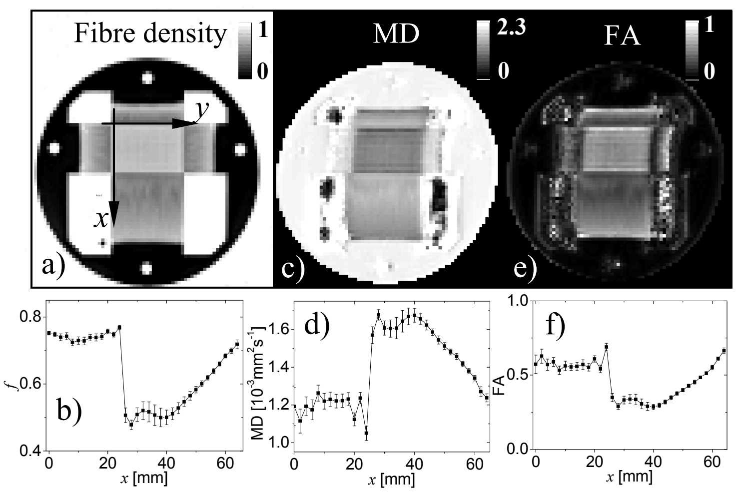

Figure 2. The maps (a, c, e) and the corresponding profiles along x (b, d, f,) of f (a, b), MD (c, d), and FA (e, f). The units of MD are 10^{-3}mm^{2}s^{-1}.

Figures 2c and 2e show, respectively, the maps of the mean diffusivity (MD) and fractional anisotropy (FA) in the side 2. Figures 2d and 2f show the corresponding profiles along x. The profiles tend to be constant in the cross-fibre region but vary in the parallel-fibre region: MD decreases and FA increases with increasing x in correlation with increasing f, Fig. 2b. In the parallel-fibre region, the main eigenvalue of the diffusion tensor was independent of both f and of $t_d = \Delta\text{-}\delta/3$. In contrast, the perpendicular eigenvalue λ_{perp} was found to depend significantly on f and t_d, see Fig. 3a. Deviations from Gaussian diffusion were observed in diffusion attenuations above b = 1000 s mm^{-2}. Quantitative characterization of such deviations was performed by means of DKI [3] in the range of $b \leq 3000$ s mm^{-2}. The values of mean kurtosis, K, as a function of f and t_d are plotted in Fig. 3b for the parallel-fibre region. One can see that K increases with increasing f and decreasing t_d.

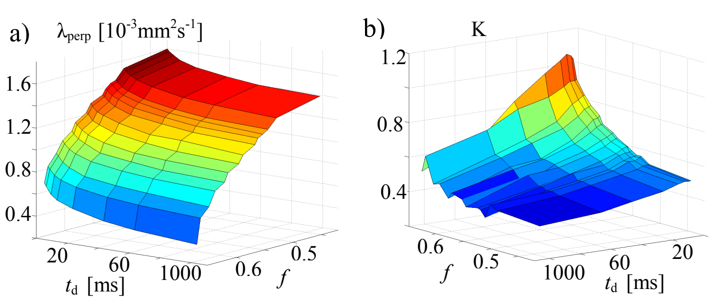

Figure 3. Dependence of λ_{perp}, a) and K, b) on f and t_d.

Conclusions

A novel diffusion phantom was constructed which exhibits a gradient of fibre density in the parallel-fibre region. This design allows us to access various degrees of anisotropy within the same sample and under the same physical conditions. In this work, DTI and DKI analysis of the constructed phantom was performed for different observation times using the stimulated echo pulse sequence. In particular, the deviations from Gaussian diffusion were shown to depend both on fibre density and the observation time.

References

[1] E. Fieremans et al., *Phys Med Biol* **53**, 5405 (2008); [2] M. Perrin et al., *Phil. Trans. of the Royal Society B* **360**, 881 (2005); [3] J.H. Jensen et al., *Magn Reson Med* **53,** 1432 (2005).