Phantom optimization for diffusion tensor magnetic resonance imaging.

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Introduction

The main application of diffusion tensor imaging (DTI) is to study the white matter geometry in vivo. To validate this technique, we have proposed a flexible hardware phantom by using parallel fibers of woven strands tightly held together by a shrinking tube [1]. In this abstract, the short- and long-time diffusion behaviour of extra cellular diffusion between parallel fibers is modelled by Monte Carlo simulations and experimentally evaluated. The results show that the packing density and the fiber diameter are the most effecting parameters in the phantom design for DTI.

Materials and methods

The phantom fascicle consists of parallel fibers of Dyneema® D1 which are tightly held together by a flexible, polyolefin low-temperature shrinking tube. The wires have a diameter of 100 µm and are made of woven strands of Dyneema fibers with a diameter of 15±3µm. The fiber density α was obtained by measuring the proton density: α = 1 - proton density = 0.66 ± 0.07. The time-dependent apparent diffusion coefficient (D_{app}) was measured with a diffusion weighted stimulated echo sequence (PFG-STEAM) on a Brüker Minispec mq20 benchtop NMR system (0.5T) equipped with a pulsed gradient unit. Varying diffusion weighted gradients (0 up to 2T/m) were applied perpendicular to the fiber directions for increasing diffusion times (Δ = 0 up to 150ms, δ = 0.2 ms). $D_{app}(\Delta)$ was obtained by a linear fit of the ln[S(b)/S(b=0)]-curve.

Consequently, four fiber materials (silk yarn, reeled silk filaments, Dyneema® D1and Dyneema® D2) with different fiber diameters (35±5µm, 35±5µm, , 15±3µm, 18±3µm) are used to fabricate phantom fascicles with varying fiber densities. Fractional anisotropy and proton density measurements were performed on a 1.5T Siemens Symphony scanner equipped with an 8 element head coil. Proton density measurements were done with a multiple spin echo sequence with 32 contrasts (TE= 50 ms, 100 ms … 1600 ms) and a TR of 10s. Test tubes with varying concentrations of deuterium oxide (D_2O) in water were used as concentration standard. Diffusion weighted EPI-imaging was performed in 6 directions with b-factors of 0 and 700 s/mm² and diffusion time Δ = 32ms.

Results

Figure 1 shows the time dependent decay of D_{app} for the Dyneema® sample. Figure 2 shows the measured FA as a function of the proton density values for the tested fiber materials. Figure 3 presents a model that estimates the upper limit of the maximum feasible fractional anisotropy value for Δ = 32 ms in diffusion phantom fibers with a given diameter and fiber density.

Discussion

Figure 1 and 2 demonstrate that the diffusion coefficient and the fractional anisotropy within the prepared diffusion phantoms are functions of the diffusion time Δ, the diffusion coefficient in free water D_0, the fiber diameter and the fiber density.

According to the theory of diffusion in porous media, the diffusion behaviour in short-time regime, i.e. $(D_0 t)^{1/2}$ < pore size, is determined by the surface-to-volume ratio S/V [2]. In the long-time regime D_{app} becomes constant and can be described by the tortuosity, λ [3]. To study the diffusion process between the fibers, Monte Carlo simulations were performed which model the 2D-random movements of particles in a plane covered with randomly placed discs. These simulations affirmed that the short-time regime is mainly dependent on the fiber density α and the fiber diameter. In the long-time regime the tortuosity coefficient is mainly determined by the fiber density α and the packing geometry. An analytical formula was derived for the short-time behaviour and fitted through the experimental data in figure 1: the obtained fiber diameter (15µm) and fiber density (0.6) were in agreement with the actual measured parameters (diameter = 15 ± 3µm and α = 0.66 ± 0.07). Based on the MC-simulations, a simplified analytical model (with parameters α, fiber diameter, D_0 and diffusion time Δ) was formed to model the diffusion and the fractional anisotropy within the diffusion phantoms. Figure 3 illustrates this model for Δ = 32 ms.

Conclusion

The short- and long-time extra cellular diffusion behaviour in diffusion phantoms is studied by MC-simulations and experimental data. A model is derived which provides, for given fractional anisotropy and proton density, information about the maximum diameter and minimum diffusion time Δ to use when performing DTI on the diffusion phantom.

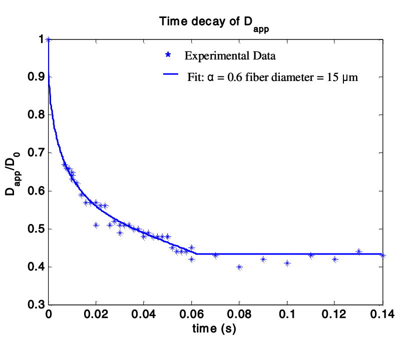

Figure 1:
Time decay of the apparent diffusion coefficient.

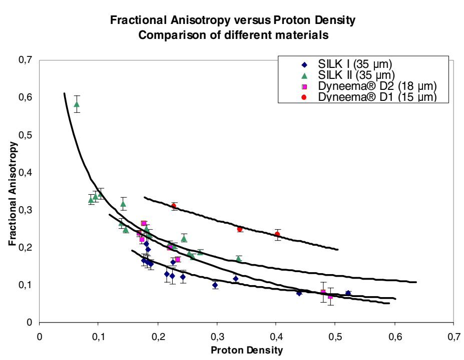

Figure2:
Fractional Anisotropy value versus proton density: comparison of different fibers diameters.

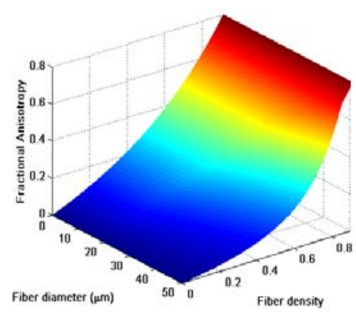

Figure 3:
Simulation of the fractional anisotropy as a function of the fiber diameter and the fiber density for Δ = 32 ms.

References

[1] Fieremans et Al. Proc. ISMRM 2005, 1301; [2] Mitra et Al. Phys. Rev. Lett. **68**, 3558 (1992); [3] Szafer et Al. MRM **33**, 697 (1995).