The Open-Access Journal for the Basic Principles of Diffusion Theory, Experiment and Application

Design of Anisotropic Diffusion Hardware Fiber Phantoms

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(received 11 July 2008, accepted 12 January 2009)

Abstract

A gold standard for the validation of diffusion weighted magnetic resonance imaging (DW-MRI) in brain white matter (WM) is essential for clinical purposes but still not available. Synthetic anisotropic fiber bundles are proposed as phantoms for the validation of DW-MRI because of their well-known structure, their long preservability and the possibility to create complex geometries such as curved and fiber crossings. A crucial question is how the different material properties and size of the fiber phantoms influence the outcome of the DW-MRI experiment. Several fiber materials are compared in this study. The effect of surface relaxation and internal gradients on the SNR is evaluated. In addition, the dependency of the fiber density and fiber radius on the diffusion properties is investigated.

Keywords

Diffusion, Magnetic Resonance Imaging, phantom, validation, simulation

1. Introduction

Anisotropic fiber phantoms have been proposed for the validation of diffusion weighted magnetic resonance imaging (DW-MRI) on clinical MR-scanners [1] and to test fiber tracking algorithms, particularly in the case of fiber crossings [2,3,4]. Several fibers have been used: rayon [2], Dyneema [1,3,4], hemp, linen, acrylic fibers [3], … Choosing the appropriate fiber material requires insight in the factors influencing the signal-to-noise ratio (SNR) of the DW-MRI experiment and the measured diffusion properties. The effect of the fiber diameter and density on the diffusion properties have been studied in this study. In addition, the surface relaxivity of several fiber materials has been measured and its effect on the SNR and the diffusion properties has been evaluated. The role of magnetic susceptibility has also been addressed.

2. Materials and Methods

2.1. Phantom manufacturing

Fiber phantoms were manufactured with different fiber types: Dyneema® (∅ 8 µm), nylon (∅ 32 µm) and glass fibers (∅ 3.5 µm). The diameters of the fiber were measured with scanning electron microscopy (SEM). Straight fiber bundles were manufactured containing a varying number of fibers. The fiber bundles were immersed in water and surrounded by a shrinking tube to pack the fibers densely together. Air bubbles were removed using a vacuum chamber.

2.2. MRI experiments

MRI-measurements were performed at 20°C on a Siemens Trio scanner (3T) equipped with an 8-element head coil.

The SNR in the fiber phantoms is mainly determined by the T_2 relaxation time and the proton density (PD) fraction in the fiber phantoms. T_2- and PD-measurements were measured with a multiple spin echo sequence with 32 contrasts, an inter-echo time ΔTE of 40 ms, a TR of 10 s and a band width (BW) of 130 Hz/Px. The resolution was 0.9 mm × 0.9 mm × 2 mm. Measurements were performed for varying angles between the fibers and the B_0-field.

Diffusion weighted imaging was performed in 60 directions with *b*-factors of 0 and 700 s/mm² using a TRSE-EPI sequence with a BW of 1275 Hz/Px, a TR of 8 s and a TE of 93 ms. The resolution was 2 mm × 2 mm × 2 mm. The diffusion weighted images were used to derive the diffusion tensor and calculate the fractional anisotropy (FA).

3. Results

The measured T_2-values as a function of the PD are shown in Fig. 1 for phantoms of the three tested fiber materials with varying density and parallel aligned to B_0. Fig. 2 shows the measured T_2 as a function of the angle between the fibers and the B_0 field for fiber bundles with a measured PD of 70 %. The measured FA as a function of the PD is plotted in Fig. 3.

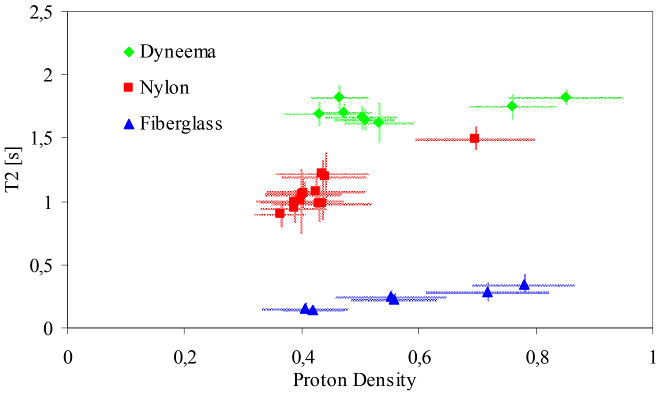

Fig. 1: The T_2-relaxation time as a function of the proton density for fiber bundles made of the three tested materials with varying density.

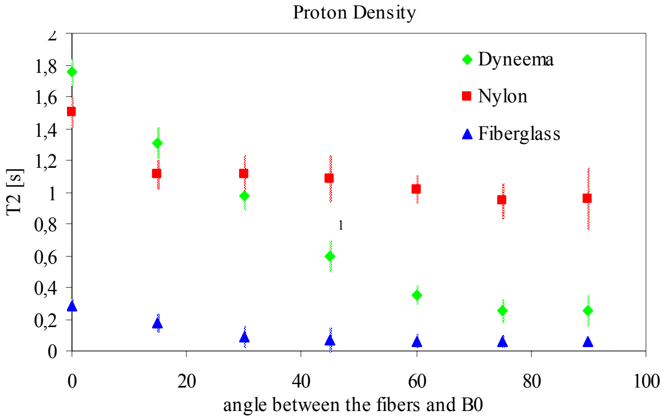

Fig. 2: The T_2-relaxation time as a function of the angle between the fibers and B_0 for fiber bundles made of the three tested fiber materials with a proton density of 70 %.

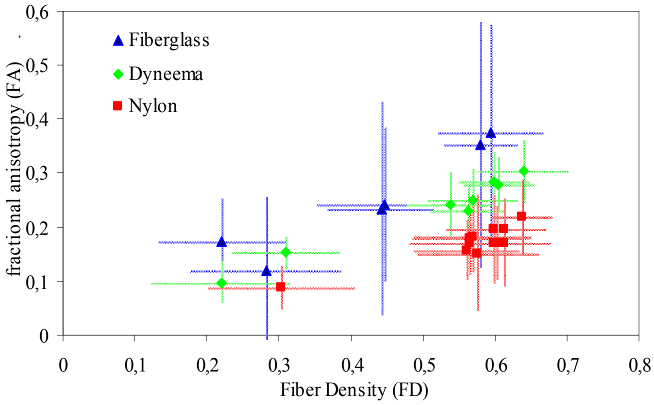

Fig. 3: The FA-values of fiber phantoms made of the three tested materials as a function of the fiber density, which is equal to 1 – PD.

4. Discussion

The PD in the bundles is rather low in comparison with WM (around 0.65) since the fibers used in the phantoms are plain whereas the DW-MRI signal in WM originates from the water in both the intra- and extracellular space. The loss in signal due to the lower PD can be compensated by a longer T_2 than the T_2 of WM (85ms). The surface relaxivity influences the T_2-relaxation time as shown in Fig. 1. The T_2-relaxation time of the water molecules in the phantoms increase with increasing proton density. The T_2 depends differently on the proton density for tested fiber materials due to different fiber surface relaxivities. Among the tested materials, Dyneema® is highly hydrophobic and has a low surface relaxivity resulting in the highest T_2. In addition, local differences in magnetic susceptibility between water and phantoms materials induce local field inhomogeneities which results in an additional decrease of the T_2. The local field inhomogeneities and the effect on the T_2 increase with increasing angle between the fibers and B_0 as shown in Fig. 2. The decrease in T_2 when changing the angle between the fibers and B_0 depends on the difference in magnetic susceptibility between fiber and water. Nylon has the closest susceptibility to water.

The FA increases with increasing fiber density or decreasing proton density for each fiber material. Bundles with a smaller fiber diameter have a higher FA when comparing bundles with the same density. Glass fibers and Dyneema® have FA-values that come closest to those observed in brain WM, typically around 0.7. The results here confirm the simulations and experimental verification of the diffusion inside the fiber phantoms as performed in [5].

5. Conclusion

Anisotropic fiber phantoms are proposed for the validation of DW-MRI on clinical MR-scanners. The fiber density and fiber diameter are two important factors that determine the diffusion properties such as the FA, while the SNR is determined by the surface relaxation and the magnetic susceptibility through their effect on the T_2-relaxation. The most appropriate fiber bundles to mimic diffusion measurements in brain white matter are densely packed fiber bundles made from a hydrophobic material with a susceptibility close to water.

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