

Anisotropic Fiber Phantom for DTI validation on a clinical scanner

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Introduction

Diffusion tensor imaging (DTI) is a powerful tool for non-invasive investigation of microstructure and has been successfully applied to detect different white matter diseases [1]. DTI-based fiber tracking gives insights into the complex architecture of the brain. However, validation of DTI results and analysis of variability for different MR-systems for realistic fiber architecture remain challenging and require suitable test phantoms. For isotropic diffusion the ADC can be well verified on water and other pure liquid phantoms [2]. Verification of tensor measurements and application of different fiber tracking algorithms with anisotropic diffusion requires a phantom with well known structure and anisotropic properties. Several fiber phantoms have been proposed recently [3-6], which have several drawbacks such as susceptibility artifacts for EPI sequences caused by gas bubbles and small values for fractional anisotropy (FA). In this work, the feasibility of using various fiber phantoms for calibration measurements on a clinical scanner was investigated and their suitability for application of fiber tracking was tested.

Material and Methods

Four different types of fibers were used for the phantoms: hemp (H) (natural fibers), rayon (R) (\varnothing 100 μ m, approx. 5000 fibers), linen (L) (\varnothing 340 μ m, approx. 1350 fibers) and dyneema (Dy) (\varnothing 200 μ m, approx. 4000 fibers). Dy-fibers are braided strands of polyethylene fibers with a diameter smaller than 10 μ m. For all phantoms, fiber bundles were held together by a rayon raffia ribbon, which was tightly wrapped around the parallel fibers to generate a cross section of approx. 450 mm². In order to prevent contamination by air bubbles, the wrapping of the fiber bundles was performed under water. Additionally, a fiber crossing phantom was prepared with two crossing Dy-fiber bundles at an angle of approximately 60°. Since diffusion measurements are very sensitive to motion, the phantoms were fixed to a frame that was put into a box filled with water (Fig.1). To ensure reproducibility of our measurement results, several Dy-fiber phantoms were generated and analyzed. All experiments were performed on a 3T system (Trio, Siemens, Germany) using an 8 element head array coil. A standard DW EPI sequence was used and extended to 61 diffusion encoding directions and b-factors of 0 and 1000 s/mm². Spatial resolution was 2 \times 2 \times 2 mm³ or 1.4 \times 1.4 \times 3 mm³. The total scan time was less than 10 min. For FA analysis mean diffusivity (D'), signal intensity (SI) and the direction of the highest eigenvectors were calculated with in-house written software based on Matlab.

Results

Color-coded FA maps for the four different phantom materials with straight fiber bundles are presented in Fig.2. Color coding of FA (x- (red), y- (green) and z-direction (blue)) for the R, H and L phantoms indicate a considerable spatial variability of local FA. In contrast, the Dy phantom demonstrates a very homogeneous FA and thus fiber structure along z-direction (blue). These findings are supported by mean FA which was calculated for all phantoms (Table 1) and resulted in a value around 0.3 with a relative standard deviation of more than 50% for R, H and L. The FA in Dy was twice as large with a slightly reduced standard deviation (std). In addition, D' and the corresponding std was small in comparison to the other phantoms. The SI in the images measured with b-factor = 0 was almost evenly low for R, H and L fibers and much higher for Dy. The direction of the highest eigenvectors in R, H and L was widely varying, while analysis for Dy revealed strong alignment along fiber bundle direction. For the Dy phantom the distribution of the highest eigenvectors was Gaussian distributed with a full width at half maximum of 9°. Measurements in several Dy-phantoms showed a high reproducibility of mean diffusivity, FA and the distribution of the highest eigenvectors. Results of DTI measurements for the fiber crossing phantom are illustrated in Fig.3 and display higher D' values in the crossing region if compared to areas outside the crossing. Fig.4 shows the FA map of the crossing phantom, inside the crossing (top) and outside (bottom). The FA index inside the crossing was found to be much lower than outside the crossing. Diffusion tensors in the crossing region were disk shaped and the direction of the highest eigenvectors varied strongly.

Discussion

The FA and mean diffusivity obtained for the R phantom are in agreement with reported results in [5]. Our results for the Dy-fiber phantoms are different from the observations presented in [6]. In this study, higher FA values for Dy-fibers have been determined without noticeable artifacts due to susceptibility. These discrepancies may be related to differences in Dy-fiber architecture. There are several types of Dy-fibers available from different manufactures, which might have different MR-significant properties. However, results for Dy phantoms presented here were highly reproducible. If the wrapping was tight enough, stronger wrapping hardly changed the diffusion parameters. R, H and L appear to be less suitable for fiber phantoms than Dy. The differences in FA, D' and the spreading of the highest eigenvectors might be caused by variations of the filament direction in these fibers as well as local deformations of the fibers (at least for H and L fibers of natural origin). Additionally, unavoidable air bubbles in R, H and L led to susceptibility artifacts. Probably these air bubbles can be explained by the highly hydrophilic nature of the fibers leading to diffusion between and inside the fibers. Therefore diffusion is not restricted to a high degree and detection of anisotropy will be difficult. In contrast, dyneema fibers are highly hydrophobic, enabling diffusion only in the interstitial space.

References

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Fig.1. Experimental setup. Phantoms fixed to a frame in a box filled with water.



Fig.2. Color coded FA map in a coronal slice along the center of fiber bundles. From left to right: R, H, L and Dy phantom.

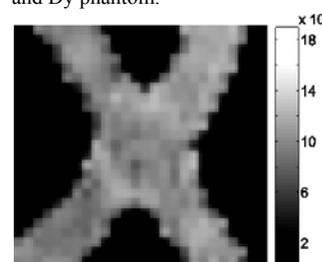


Fig.3. D' map in a coronal slice of fiber crossing phantom with Dy-fibers.

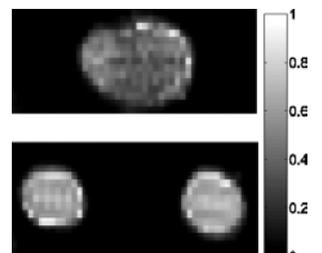


Fig.4. FA map in transversal slice. Top: inside the crossing. Bottom: outside the crossing

Fiber	FA	D', x10 ⁻³ mm ² /s	SI _{fiber} / SI _{water}
rayon	0.30 ± 0.17	1.58 ± 0.59	0.07
hemp	0.29 ± 0.15	1.78 ± 0.60	0.07
linen	0.33 ± 0.20	1.68 ± 0.66	0.08
dyneema	0.68 ± 0.13	1.19 ± 0.21	0.40

Table1. phantoms diffusion parameters