# Development of a hindered-diffusion-dominant DTI phantom made of polyethylene fibers: Comparison with a restricted-diffusion phantom.

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**Target Audience**

People in the fields of DTI application, physics, and technology.

**Introduction**

Diffusion tensor imaging (DTI) is now performed at many clinical sites to investigate brain microstructure and structure-related pathologies. To ensure that data quality is maintained across multiple sites and manufacturers it is desirable to have a phantom with in vivo-like diffusion characteristics for DTI quality control (QC). Some restricted-diffusion phantoms, such as capillary plates (CPs),[1] have been proposed for this purpose but the diffusion characteristics differ from those found for in vivo tissue and are very expensive. As an alternative, we have developed a hindered-diffusion-dominant DTI phantom made of polyethylene fibers. This study investigates the diffusion characteristics of this phantom and evaluates its suitability for DTI QC in comparison to a CP phantom.

**Materials and Methods**

_Polyethylene fiber (Dy) phantom_: Polyethylene fibers (diameter < 10 μm, Dyneema® (Dy), TOYOBO, Japan)[2] were bunched together with a thermal shrinkage tube and placed in a cylindrical case ($\phi$10 mm) filled with water (Fig. 1a). The whole procedure was performed underwater to prevent contamination by air bubbles.

_Capillary plate (CP) phantom_: Ten CPs were stacked in a cylindrical case ($\phi$10 mm) filled with water. The CP was manufactured to have a large number of regularly arranged glass capillaries ($\phi$20 μm, Fig. 1b). A previous diffusion-weighted MRI study has demonstrated purely restricted water diffusion in a similar CP phantom.[1]

_7T MRI_: The phantom cases were positioned parallel to each other in the bore of a 7T preclinical MRI (Bruker, BioSpin, Germany) and high resolution single-shot EPI DTI acquisitions were performed. To investigate the diffusion characteristics of the phantom, diffusion-weighted MRI was performed at multiple b-values and diffusion times (Δ). Imaging parameters were as follows: TR=3000 ms, TE=115 ms, average=1, matrix size=128x128, resolution=0.2x0.2x2.0 mm, b-value=0 to 8000 s/mm$^2$ in 13 steps, Δ=40 and 100 ms, and 30 diffusion encoding directions.

_3T MRI_: The CP and Dy phantoms were attached to a case holder and inserted into the bore of a 3T MRI (Verio, Siemens, Germany) oriented along the scanner y-axis and z-axis, respectively. DTI data was then obtained using segmented multi-shot EPI (RESOLVE)[3]: TR=5000 ms, TE=72 ms, average=2, matrix size=128x128, resolution=2.6x2.6x2.0 mm, b-value=0 and 1000 s/mm$^2$, and 12 diffusion encoding directions.

_Analysis_: After pixel-wise estimation of the diffusion tensor using the b=0 and 1000 s/mm$^2$ data, ROIs were drawn and the following quantities were calculated: fractional anisotropy (FA), mean diffusivity (MD), mean principal eigenvector (MPEV) and the angular dispersion (AD), which is a measure of the spread in angle between the MPEV and the principal eigenvector at each pixel in the ROI. The b-value dependent signal attenuations at Δ=40 and 100 ms with the MPG perpendicular to the fibers were also compared for the 7T data.

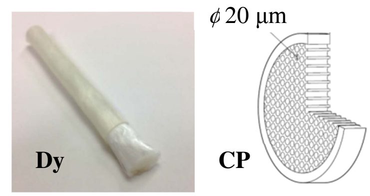


Fig. 1. (a) Dy phantom and (b) schematic of a CP.

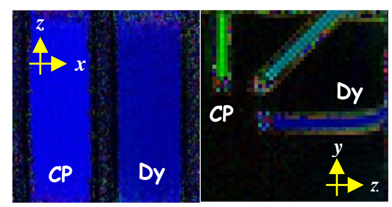


Fig. 2. Color-coded directional maps weighted by the fractional anisotropy (red: x, green: y, dark blue: z). (left) 7T and (right) 3T MRI images.

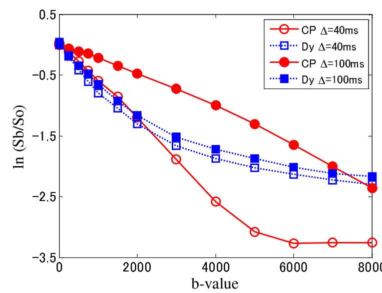


Fig. 3. b-value-dependent signal attenuation from the 7T MRI measurements.

**Results**

Color-coded directional maps were homogeneous for both the CP and Dy phantoms (Fig. 2). All FA and MD values were similar to those generally measured in vivo (Table 1). The largest FA and smallest MD were obtained for the CP from the 7T data at Δ=100 ms. All Dy and CP MPEVs were close to the expected directions and the Dy AD was always 102% - 145% of the CP AD (Table 1). The b-value dependent signal attenuation for Dy at Δ=40 and 100 ms were similar, but there was a distinct difference between those of the CPs (Fig. 3). A bi-exponential curve fitted the Dy signal attenuation well.

**Discussion**

The MPEV and AD results suggest that the Dy phantom might be useful as a clinical DTI QC phantom. There were some clear differences in the diffusion characteristics of the CP and Dy phantoms. The CP phantom was constructed from impermeable glass plate capillaries so that restricted-diffusion is dominant with no hindered-diffusion component. This is demonstrated by the b-value-dependent signal attenuation, which was dramatically altered between Δ=40 and 100 ms and the curve shape at Δ=100 ms was convex upward (Fig. 3). The relatively high FA at Δ=100 ms for the CPs is also consistent with restricted diffusion. On the other hand, b-value-dependent signal attenuation was less sensitive to Δ for the Dy phantom, implying that water diffusion is hindered rather than restricted. The fact that the attenuation is less sensitive to Δ is important when the phantom is used for quantitative comparison between multicenter MRI systems because Δ is not user adjustable on many clinical systems. The bi-exponential behavior also suggests that the diffusion characteristics are similar to those found in vivo.

Table 1. Diffusion parameters estimated for the CP and Dy phantoms.

| | 7T MRI – Diffusion Time 40 ms | | 7T MRI – Diffusion Time 100 ms | | 3T MRI | |
|---|---|---|---|---|---|---|
| | CP | Dy | CP | Dy | CP | Dy |
| FA | 0.68±0.03 | 0.55±0.04 | 0.89±0.03 | 0.61±0.03 | 0.60±0.18 | 0.52±0.04 |
| MD (x10$^{-3}$ mm$^2$/s) | 1.07±0.04 | 1.21±0.05 | 0.83±0.04 | 1.11±0.05 | 1.24±0.32 | 1.23±0.14 |
| MPEV (x, y, z) | (0.018,0.005,0.9998) | (0.025,0.003,0.9997) | (0.006,−0.015,0.9999) | (0.015,−0.009,0.9998) | (0.042,0.999,−0.008) | (0.027,0.050,0.998) |
| AD (Degree) | 2.15 | 2.87 | 1.68 | 2.43 | 4.17 | 4.28 |

**Conclusion**

A hindered-diffusion-dominant DTI phantom was developed using Dy. As it is less sensitive to diffusion time, has b-value-dependent signal attenuation similar to that in vivo tissue and is much less expensive than CPs, Dy is probably a better phantom for DTI QC than CPs.

**References**

[1] Oida T. et al. Magn Reson Med Sci. 2011;10:121-128. [2] Lorenz R. et al. Appl Magn Reson. 2008;33:419-429. [3] David A.P. et al. Magn Reson Med. 2009;62:468-475.