Accuracy of Diffusional Kurtosis Imaging in Resolving White Matter Fiber Crossings

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Introduction

Diffusion tensor imaging (DTI) is based on a Gaussian approximation to the probability distribution of water diffusion in biological tissues [1]. This limits DTI's ability to characterize complex cerebral tissue microstructure, such as in delineating intravoxel crossing white matter fiber bundles. Non-Gaussian (NG) diffusion magnetic resonance imaging methods provide a means of resolving crossing fibers by invoking more sophisticated models for quantifying the non-Gaussianity of the diffusion distribution. Diffusional kurtosis imaging (DKI) is an extension of DTI, which characterizes NG diffusion by estimating the kurtosis of the displacement distribution [2]. DKI has previously been demonstrated to resolve fiber crossings [3]; however, its accuracy has not been systematically evaluated. Here, we use numerical simulations to evaluate the accuracy of DKI in resolving two-fiber crossings and to compare this to those of diffusion spectrum imaging (DSI) [4] and Q-ball imaging (QBI) [5], two well-known NG diffusion techniques. We also investigate the accuracy of DKI and other techniques for a voxel containing a dominant fiber bundle plus a small admixture of a subdominant bundle. We estimate fiber directions based on the maxima of the analytical representations of the orientation distribution functions (ODF's). Our central hypotheses are that (a) DKI offers a reasonable tradeoff between the requirements of clinical scans and fiber delineation accuracy when compared to other NG techniques; and (b) DKI outperforms DTI in estimating the direction of a dominant fiber bundle in the presence of a subdominant bundle.

Methods

We modeled two-fiber crossings using a two-compartment model, where the diffusion in each compartment was Gaussian and there was no exchange between compartments [3]. The eigenvalues of the diffusion tensor for both compartments were set to 1.8, 0.3, and 0.3 μm^2/ms, consistent with highly anisotropic fiber bundles each having a fractional anisotropy of 0.81 and a mean diffusivity (MD) of 0.8 μm^2/ms. To test our hypotheses, fiber crossings having both equal and unequal (0.8, 0.2) water volume fractions were considered. The crossing angle was varied between 0° and 90° in steps of 5°. The DKI ODF as well as the ODF's for DSI [4] and QBI [5] were calculated from analytical representations. In a spherical coordinate system, the NG component of the DKI ODF $\psi_{\mathrm{NG}}(\hat{\mathbf{z}})$ along direction vector $\hat{\mathbf{z}}$ parallel to the z-axis is given by [3]

$$\psi_{\mathrm{NG}}(\hat{\mathbf{z}}) \approx \frac{\bar{D}}{6\pi}\int_0^{2\pi} d\phi \left.\frac{K(\theta,\phi)}{D(\theta,\phi)}\right|_{\theta=\pi/2}$$

where (θ,ϕ) are the polar and azimuthal angles, K and D are the directional kurtosis and diffusivity along the direction vector defined by (θ,ϕ), and $\bar{D}$ signifies the MD. Noting that the QBI ODF depends on the diffusion weighting *b*, it was calculated for *b* = 4000 s/mm^2 throughout the experiments. The predicted fiber directions were taken as the local maxima of the ODF. For fiber crossings with equal water fractions, the NG component of the DKI ODF was used. For estimating the direction of the dominant bundle in the fiber crossing with unequal fractions, the full DKI ODF given by the sum of the Gaussian and NG ODF components [3] was utilized.

Results

Figure 1 shows that DSI provides the most accurate estimate of the crossing angle, while DKI is roughly as accurate as QBI. We also note that none of the ODF's are able to accurately detect both fibers for crossing angles of 30° or less. Figure 2 shows the min-max normalized ODF's and the actual and estimated fiber orientations for two equal fiber bundles crossing at 60°. DSI predicts a crossing angle of 59°, which is appreciably more accurate than the predictions of the other methods, while DKI (64.6°) is almost as accurate as QBI (55.7°). Figure 3 indicates that DSI provides the most accurate estimate of the dominant fiber direction, but DKI and QBI offer comparable accuracy. DTI yielded substantially less accurate estimates for most crossing angles.

Discussion

We assessed the accuracy of resolving two-fiber crossings using analytical ODF's for DKI, DSI, and QBI. We also evaluated the accuracy of these techniques and DTI in estimating the direction of a dominant bundle intersecting with an admixture of a subdominant bundle. In both cases, the DSI ODF provided the most accurate estimates, which we believe is because DSI ODF does not, unlike the DKI and QBI ODF's, rely on auxiliary approximations. But this is achieved at the expense of requiring, in practice, high *b*-values and long scan times. Our results also suggest that the accuracy of DKI was comparable to QBI with *b* = 4000 s/mm^2. However, DKI can accomplish this with clinically more feasible maximum *b*-values of 2000 to 2500 s/mm^2, supporting our hypothesis (a) above that DKI offers a reasonable tradeoff between clinical scan requirements and fiber delineation accuracy. Our results are also consistent with our hypothesis (b) that DKI is substantially more accurate than DTI in estimating the direction of a dominant fiber bundle when an admixture of a subdominant bundle is present, which may be an important advantage for fiber tracking applications. The present study was limited to analytical ODF's and two-compartment models. Future work should address the impact of noise and other imaging imperfections on the above observations, as well as more complex crossing geometries.

References: **1.** Basser PJ, et al. Biophys J 1994; 66:259. **2.** Jensen JH, et al. MRM 2005; 53:1432. **3.** Lazar M, et al. MRM 2008; 60:774. **4.** Wedeen V, et al. MRM 2005; 54:1377. **5.** Tuch DS. MRM 2004; 52:1358.

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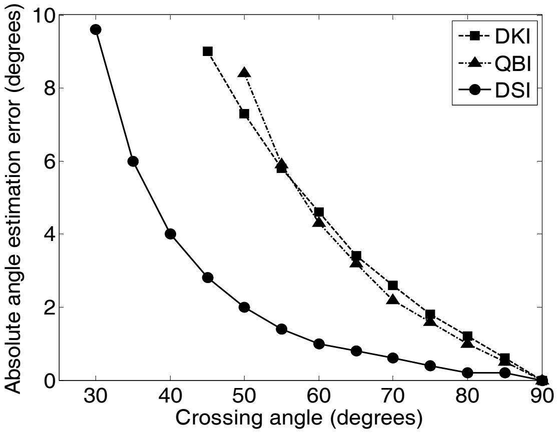

Figure 1. Absolute error in estimating the angle between two highly anisotropic fibers with equal water volume fractions as a function of the crossing angle. Data points are not shown when the error was larger than 10°.

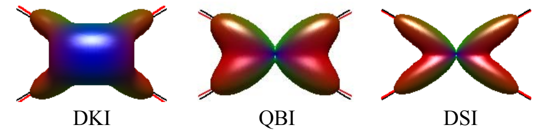
DKI QBI DSI

Figure 2. Min-max normalized ODF's for two equal fibers crossing at 60°. Black and red lines indicate true and estimated fiber directions obtained from ODF maxima.

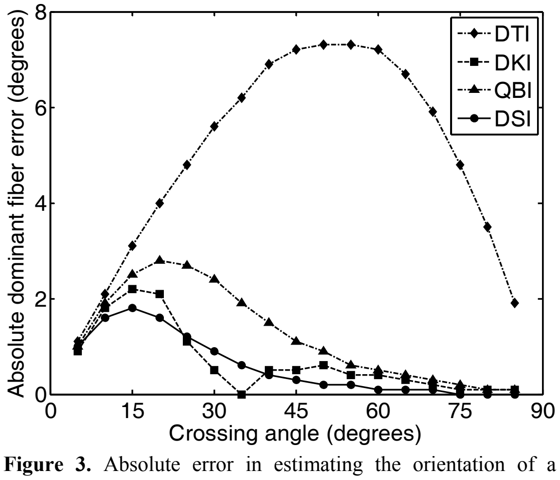

Figure 3. Absolute error in estimating the orientation of a highly anisotropic fiber intersecting with a 20% admixture of a subdominant bundle as a function of the crossing angle. The dominant fiber angle predicted by DTI can have an error of up to 7.3°. Using the DKI ODF, the maximum error is reduced to about 2.2°, which is comparable to that of DSI (1.8°), and is slightly less than that of QBI (2.8°). Note that the abrupt change of slope for the DKI curve at a crossing angle of 35° reflects a sign change for the angular error.