How Accurately Can the Diffusion Profiles Predict Multiple Fiber Orientations? - A Study on General Fiber Crossings in Diffusion MRI

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Introduction

Intravoxel multiple fibers pose a major challenge for diffusion tensor imaging (DTI) and fiber tracking techniques (1). High angular resolution diffusion (HARD) imaging (2) and q-space imaging techniques, including diffusion spectrum imaging (DSI) (3) and q-ball imaging (QBI) (4), have been developed to characterize the intravoxel fiber components. The measured apparent diffusion coefficient (ADC) and orientation distribution function (ODF) profiles are used to represent the orientations of the actual intravoxel fibers. The accuracy of these methods depends critically on the relationship between the profile local maxima and the actual fiber orientations. In previous studies, the mismatch between them and the change of the profile sharpness have been reported (4-5). However, the *quantitative* relationship between the local maxima of the diffusion profiles and the orientations of the real intravoxel fibers have not yet been thoroughly investigated. Even under ideal conditions free of noise/artifacts, it remains unclear whether any systematic angular deviation exists in the fiber orientation estimation and how it behaves with respect to various diffusion measurement conditions. Moreover, no effort has been made in comparing the accuracies among DSI, QBI and HARD techniques. Resolving these issues is necessary for reliable use of these beyond-tensor diffusion MRI techniques in delineating white matter structures. We present here a study to systematically address these issues.

Methods

A general fiber crossing model (6-7) with various intersection angles (0^o-180^o) and signal fractions (0-0.5) was used to simulate the diffusion-weighted MRI experiments with different *b* values (1000-10000 s^2/mm). Both non-exchange and well-exchange models were used to simulate the water exchange between the compartments. In each compartment, the diffusion was assumed to be cylindrically asymmetric about the fiber axis, and the ratio between the maximum and minimum ADC values was 10:1 for the intravoxel fiber. The HARD, DSI and QBI techniques were implemented to estimate the ADC and ODF profiles of the simulated general fiber crossing with various parameters. These diffusion profiles were generated on a continuous basis and no specific diffusion encoding schemes were involved in the calculation. An optimization procedure was performed on these profiles to determine the orientation of the local maxima. The angular deviations of these diffusion profiles were measured by the angle between the the estimated local maxima and the known corresponding fiber orientations.

Results and Discussions

In Fig.1, the deviation angles $\delta\theta$ of DSI, QBI and ADC methods are compared with various intersection angles Ω_{12}, under the conditions of equal signal fraction (f = 0.5), fixed *b* value of 5000 s^2/mm and without water-exchange. It is shown that the two ODF methods (i.e. DSI and QBI) have similar behavior in the angular deviations, but different from that of the ADC method. The deviation angles of DSI and QBI methods are convergent to zero when the intersection angle approaches to 90^o, 0^o or 180^o, while reaching their peak values when the intersection angle is around 42^o or 138^o. Comparatively, QBI has slightly smaller angular deviations than that of the DSI. For ADC method, the angular deviation is proportional to the intersection angle, and reaches the peak magnitude of 45^o when the intersection angle around the 90^o point. In Fig.2, the effects of *b* value on the behavior of the deviation angle are illustrated with fiber crossings of equal fraction (f= 0.5) and no water-exchange. The deviation angles of DSI, QBI and ADC at various *b* values are illustrated in Fig.2 A, B and C, respectively. In general, the angular deviation is lower when a higher *b* value is used. Meanwhile, the intersection angle corresponding to the peak deviation angle shifts slightly to the lower end (for the acute intersections) with higher *b* values. For high *b* values, there is an angular zone where the deviation magnitude is negligible, centered at the orthogonal intersection. Little *b*-factor effect is found for the ADC method. In Fig.3, the effects of signal fraction on the angular deviation are shown for non-exchange fiber crossings with varying fractions (f = 0~0.5) at b = 3000 (s^2/mm). The deviation curves of DSI, QBI and ADC at different f values are plotted in Fig.3 A, B and C, respectively. For all methods, the deviation at any intersection angle reaches the highest magnitude when the signals are equally contribute (i.e. f = 0.5). The deviation angle curve converges to zero when the fraction f approaches 0 (i.e. the fiber crossing degenerates to a single fiber). It is observed again that the angular deviations of the QBI method illustrate a similar pattern as that of the DSI method, yet the deviation angle magnitude is slightly smaller for QBI with the same parameters. In Fig.4, subfigure A, B and C illustrate the deviation angle curves of an equal fraction fiber crossing simulated under the well-exchange condition for the DSI, QBI and ADC methods, respectively. The curves corresponding to different *b* values completely overlap, indicating that the change of *b* values has no effects on the angular deviation curve. It is shown that the deviation curves are almost identical for the three different methods.

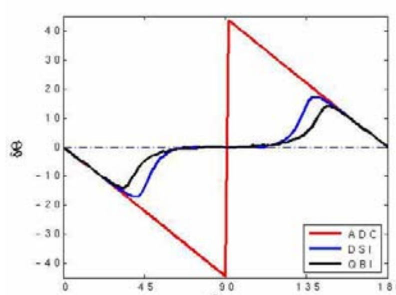

Fig.1 Angular deviation curves of a typical fiber crossing for ADC, DSI and QBI methods.

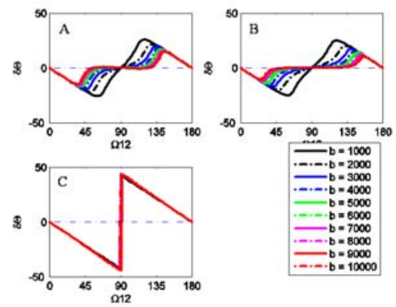

Fig.2 Effects of b factors on the angular deviations for DSI, QBI and ADC methods.

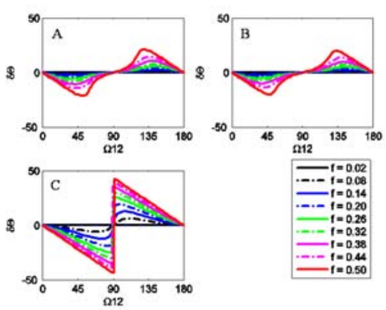

Fig.3 Effects of fraction f on the angular deviations for DSI, QBI and ADC methods.

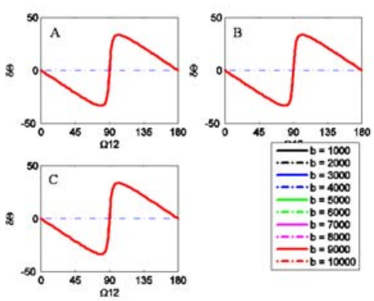

Fig.4 The deviation curves of a well-exchange fiber crossing for DSI, QBI and ADC methods.

In summary, the present study has systematically investigated the angular deviations between the local maxima on different diffusion profiles and the actual fiber crossing orientations for DSI, QBI and ADC methods. For a typical non-exchange fiber crossing with equal fraction, the angular deviation of ODF methods approaches the peak when the intersection angle is around 45^o or 135^o, and the deviation is minimal around the 90^o intersection. Differently, the ADC method has a deviation angle proportional to the intersection angle, with a peak at the orthogonal (90^o) intersection. The QBI method demonstrates a slight, yet consistent, advantage of less deviation over the DSI method under the same conditions. Higher *b* values are favorable for achieving lower angular deviations in both DSI and QBI methods, but have little effect on the ADC method. It is also indicated that the differences between the ADC and the ODF methods and the effects of *b* values vanish if water in fiber crossing is well-exchanged.

References

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