Mapping the Orientation of Intra-voxel Crossed Fibers Based on the Phase Information of the Diffusion Circular Spectrum

W. Zhan[1], E. A. Stein[1], Y. Yang[1]

[1]Neuroimaging Research Branch, National Institute on Drug Abuse, NIH, Baltimore, MD, United States

Synopsis

The diffusion circular spectrum mapping (DCSM) was recently proposed to map the fiber crossings in human brains, but the orientation of the intra-voxel fiber-crossings remained unknown. The present study aims to solve this problem by utilizing phase information of the 4th order circular spectrum to estimate the orientation of the intra-voxel crossed fibers. Both computer simulations and diffusion MRI experiments were conducted to validate this method. Results indicated that the estimated intra-voxel crossed fibers shown a clear consistency with the surrounding fiber tracks. This method could be used to improve current fiber-tracking techniques in the presence of fiber crossings.

Introduction

A challenge in diffusion tensor imaging (DTI) is the difficulty brought by fiber crossings in that the major eigenvector of the tensor could be seriously biased from the real orientation of the actual fibers and that the DTI map is unable to distinguish a fiber crossing from an inherent planar tensor [1-3]. To overcome this difficulty, we have proposed the diffusion circular spectrum mapping (DCSM) method that applies a Fourier transform to the apparent diffusion coefficient (ADC) distribution on the circle spanned by the major and median eigenvectors [2]. We have demonstrated that the magnitude of the 4th order circular harmonics can be used as an index to map the "strength" of the orthogonal fiber crossings [2]. However, the orientation of the intra-voxel crossed fibers in these voxel remains unknown. This study is to estimate the orientation of intra-voxel crossed fibers based on the phase information of the diffusion circular spectrum. Both computer simulations and in vivo MRI experiments were performed to validate this method. Results indicated that the estimated orientation of intra-voxel crossed fibers exhibited a clear consistency with the fiber tracks in the surrounding voxels.

Methods

Phase Information. On the plane spanned by the major and medium eigenvectors, the ADC profile of an orthogonal fibers crossing has a 4-leave pattern, which can be described as a sinusoid function with an angular frequency of 4 [2]. It has been demonstrated that the magnitude of the 4th order harmonic of the sinusoid function characterizes the "strength" of the fiber crossing [2]. Similarly, the phase of the 4th order harmonic represents the "shift" of the sinusoid function, i.e. the rotation of the 4-leave profile on the plane. Therefore, the DCSM phase information can be used to determine the orientation of the intra-voxel crossed fibers.

Phantom Simulations. The same digital phantom as that in previous study [2] was used to simulate objects with various diffusion patterns, such as spherical objects with isotropic and planar diffusion patterns, and cylinder objects with linear diffusion pattern arranged parallel to the cylindrical axis. Fiber intersection and dispersion were simulated in the areas of two objects crossing each other. The diffusion-weighted images (b=2500 s/mm^2) were simulated on 128 diffusion encoding directions equally spaced on a sphere, and a non-diffusion image was also generated.

In Vivo Experiments. The brains of normal human subjects were scanned on a 3T Siemens Allegra scanner using a spin-echo EPI sequence with a b value of 2500 s/mm^2 at the 128 diffusion encoding directions. TR/TE = 1300/136 ms, FOV = 24x24 cm^2, and matrix size = 128x128. A total 10 repetitions were acquired to ensure a SNR = 84 after averaging. Five imaging slices (4 mm thickness with 1 mm gap) were placed in a coronal orientation covering the pones area and approximately parallel to the brain stem.

Data Processing. For each voxel, regular diffusion tensor and the circular spectrum were calculated as described in [2]. The brain area of fiber crossings were highlighted by closed white curves on the background of the corresponding directionally encoded color (DEC) map [4] by a threshholding procedure onto the magnitude of the 4th order DSCM map. For each selected voxel, the intra-voxel crossed fibers were illustrated by two crossed line segments in a 3D perspective. For voxels without fiber crossing, the major eigenvector was illustrated in the same perspective manner with a single line segment.

Results and Discussions

A selected partion of the digital phantom is plotted in Fig.1 to illustrate the simulation results in the fiber intersection area (A). In Fig.1a, only the major eigenvector is plotted in each voxel representing a typical result of regular DTI technique. In Fig.1b, the intra-voxel crossed fibers estimated from the phase information are illustrated in each voxel where the 4th-order DCSM value is significant. It is shown in Fig.1a that the major eigenvector in a fiber crossing voxel can be serious biased from the actual fiber orientations and that a small disturb to the crossing angle may result in an abrupt change of the major eigenvector. In Fig.1b, as a comparison, the estimated intra-voxel crossed fibers are clearly consistent with the fiber tracks in neighboring voxels without crossing.

A typical slice of the *in vivo* results is shown in Fig.2 where the voxels with fiber crossing are highlighted on the DEC map. A brain area selected by a yellow square is enlarged and illustrated in Fig.3 with the estimated intra-voxel crossed fibers. Similar to the simulation results, the estimated intra-voxel crossed fibers show a clear consistency with the surrounding fiber tracks. Fiber tracking procedures based on the major eigenvector would follow a wrong trajectory over a fiber crossing, whereas the estimated intra-voxel crossed fibers by DCSM phase information could provide a more accurate direction for the tracking procedures.

References

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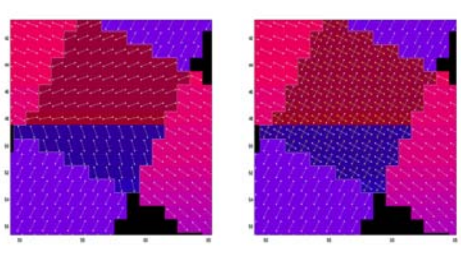


(a) (b)

Fig.1: Two linear objects crossing each other. (a): only the major eigenvector is shown; (b): the estimated intra-voxel crossed fibers are shown.

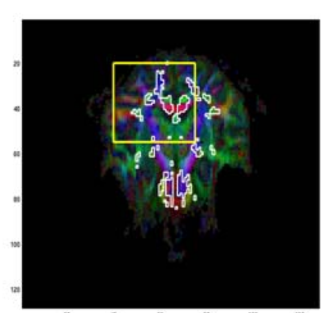
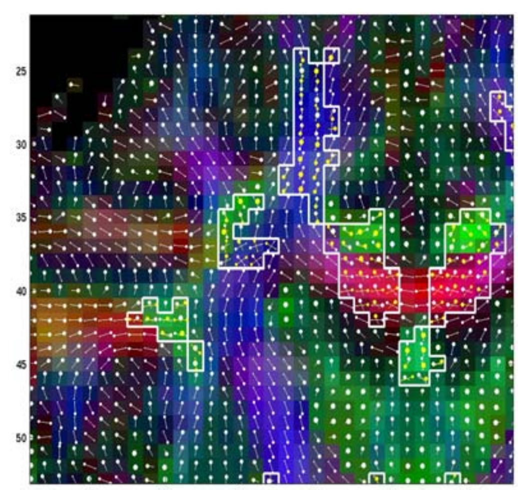


Fig.2: A coronal slice of the human brain with two selected partial areas: fiber crossing voxels are highlighted on the background of DEC map.



3: Partial areas of the brain with estimated intra-voxel crossed fibers.