Impact of Partial Volume Effect on Fiber Coherence Index (FCI) Calculation: A Simulation Study

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Introduction

Over the past few years, applications of diffusion tensor imaging (DTI) have been expanded considerably *(1,2)*. Most of DTI applications rely on scalar diffusion tenor parameters, such as the mean diffusivity, fractional anisotropy (FA), and relative anisotropy (RA) *(3)*. Recently, it was reported that a vector-based parameter, known as fiber coherence index (FCI), was also useful to probe white-matter structural integrity and reveal the underlying pathologic changes *(4)*. Unlike scalar diffusion tensor parameters, FCI requires correlating the principal diffusion eigenvector for a voxel of interest with that of its neighbors. This operation is particularly sensitive to the partial volume effect, especially considering that diffusion tensor images at the present stage are typically of low spatial resolution (e.g., 2x2x5mm^3). In this study, we have carried out a number of computer simulations to investigate the impact of partial volume effect on FCI calculations. Through these simulations, we aimed at a better understanding of the potential and pitfalls of using FCI for clinical studies.

Methods

The FCI for a voxel of interest *j* is defined by Eq. [1], where *i* is the index of the voxels in the close proximity of the j^{th} voxel, *g (i, j)* is a weighting function that defines the spatial extent over which the summation is performed, λ is the fiber orientation vector, and *N* is the total number of voxel pairs used for the vector inner product calculation. The fiber orientation vector for voxel *j* (λ_j) and its neighbors (λ_i) can be approximated by the principal diffusion direction in the corresponding voxels. To calculate a regional FCI (r-FCI) within an ROI containing *M* voxels, the individual FCI values can be simply averaged. For a straight, coherent fiber, FCI value is theoretically equal to 1.0. In practice, however, the actual FCI can deviate from the ideal value due to the partial volume effect resulting from low spatial resolution. To understand how the insufficient spatial resolution can bias the FCI calculations, we performed 2D computer simulations for three types of fibers: (a) straight fibers, (b) bent fibers, and (c) branching (or crossing) fibers (Fig. 1). In each case, the fiber thickness was varied from 0.5 to 6mm, while the spatial resolution was held constant at 2x2mm^2. For each fiber type with a specific thickness, a 2048x2048 grid was created over 25.6 cm FOV. This grid was re-sampled to create an image matrix of 128x128, with the fiber orientation in each image pixel determined from all grid elements in that pixel (Note that each pixel contains 16x16 grid elements). The vectors for the region outside the fiber were generated based on a random normal distribution. In each case, an ROI containing 3x3 pixels were manually selected (Fig. 1), and the FCI for the central pixel evaluated. The resultant FCI value was obtained as an average of 20 simulation runs.

$$FCI_j = \frac{1}{\sum_{i=1}^{N} g(i,j)} \left| \sum_{i=1}^{N} \left(\lambda_j \bullet \lambda_i \right) g(i,j) \right| \qquad [1]$$

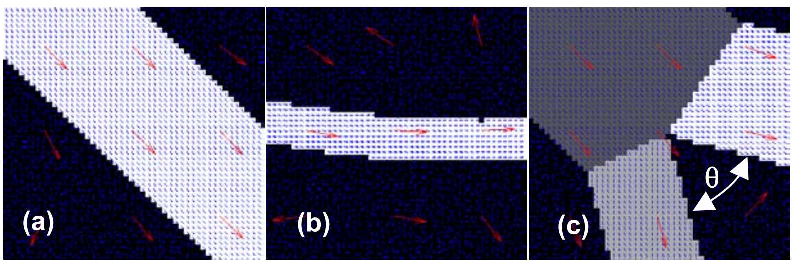

Fig. 1 ROIs containing 3x3 pixels for straight (a), bent (b), and branching (c) fibers. The red arrows represent the eigenvector at each pixel. θ in (c) is the branching angle.

Results

Simulation results for the straight and bent fibers are given in Fig. 2a, which shows the variation of FCI values with respect to fiber thickness. At a spatial resolution of 2x2mm^2, the FCI at the center of a straight fiber exhibited substantial error, unless the fiber diameter was greater than ~4mm. After this critical value, the FCI began to approach to the theoretical value of 1.0. For the bent fibers, the FCI approached to the theoretical value of 1.0 when the fiber thickness exceeded ~3mm. Although these results are specific to the geometry and fiber orientation selected in the simulation, we have generally observed that the fiber thickness needs to be approximately two times that of the pixel dimension in order to obtain a reliable FCI value.

Figure 2b displays the FCI of the branching point versus the angle θ between the branching fibers (Fig. 1c). As expected, the FCI decreased as θ increased. But the degree of FCI reduction was less than 3% at a branching angle of 30º, and less than 14% even at a larger angle of 60º.

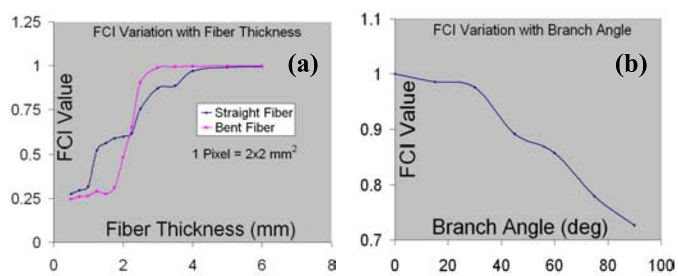

Fig. 2 FCI variation vs. fiber thickness (a) and branching angle (b).

Conclusions

In this study, we have simulated a limited number of fiber size, geometry, and spatial arrangement. However, the simulation method can be applied to any case that may be encountered in practice. The simulation results indicate that reliable FCI can be obtained from straight and bent fibers whose thickness is approximately two times that of the pixel dimension, and from branching fibers with branching angle less than ~30º. These results will guide us to properly use FCI on specific fibers for clinical applications, when the partial volume effect is a concern.

References

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