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Exploring Local White Matter Geometric Structure in diffusion MRI Using Director Field Analysis

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Synopsis
In this abstract, inspired by microscopic theoretical treatment of phases in liquid crystals, we introduce a novel mathematical framework, called Director Field Analysis (DFA), to study local geometric structural information of white matter. DFA extracts some meaningful scalar indices related with the degree of orientational alignment, dispersion, and orientational distortion, from the Orientation Distribution Function (ODF) field reconstructed by Diffusion Tensor Imaging (DTI) or High Angular Resolution Diffusion Imaging (HARDI).

Motivations
1) Orientational dispersion has been defined based on Watson distribution modeling of ODFs in NODDI, which however cannot be applied for general ODFs.

2) Some previous works have focused on extracting local geometric information by considering spatial gradients of tensor field to describe the degree of orientation or dispersion of director and Local Orthogonal Frame.

Director and Local Orthogonal Frame. The orientations where an ODF takes its local peaks are normally considered as local fiber directions in a voxel. Considering the ODF is normally antipodal symmetric, the extracted peaks are equivalent to their negative orientations. We define a director as a vector which is equivalent with its negative. Thus, each peak is a director. We propose extracting a local orthogonal frame in each voxel with an anisotropic ODF from the detected peak field. The orthogonal frame has three orthogonal orientations. The first orientation is the principal direction where the ODF takes its global maximum. The other two orientations are in the orthogonal plane of the principal direction.

Local Distortion Indices: Splay, Bend, and Twist. Based on the liquid crystal analogy, there are three types of distortions as demonstrated in Fig. 1. 1) splay: bending occurs perpendicular to the director. 2) bend: the distortion is parallel to the director and molecular axis. 3) twist: neighboring directors are rotated with respect to one another, rather than aligned. With the local orthogonal frame \{u_1(x), u_2(x), u_3(x)\} at each voxel x obtained above, we propose three scalar indices to describe the three types of local distortions, and a total distortion index:

- Splay index: \( s = \sqrt{\left(\frac{\partial u_2}{\partial u_1}\right)^2 + \left(\frac{\partial u_3}{\partial u_1}\right)^2} \)
- Bend index: \( b = \sqrt{\left(\frac{\partial u_2}{\partial u_3}\right)^2 + \left(\frac{\partial u_1}{\partial u_3}\right)^2} \)
- Twist index: \( t = \sqrt{\left(\frac{\partial u_2}{\partial u_1}\right)^2 + \left(\frac{\partial u_3}{\partial u_1}\right)^2} \)
- Total distortion index: \( d = \sqrt{s^2 + b^2 + t^2} \)

where \( \frac{\partial u_i}{\partial u_j} \), \( i=1,2,3 \), is the spatial directional derivative of director field \( u_i(x) \) along \( u_j \), i.e.,

\[
\frac{\partial u_i}{\partial u_j} \approx \lim_{k \to 0} \frac{u_i(x + ku_j) - u_i(x - ku_j)}{2k}
\]

We first calculates three rotation matrices respectively along z, y, z axes. Then \( \frac{\partial u_i}{\partial u_j} \) is numerically approximated by \( u_i(x + u_j) - u_i(x - u_j) \), where \( u_i(x + u_j) \) and \( u_i(x - u_j) \) are approximated by the weighted mean of three rotated vectors along three axes.
Experiments
Fig. 2 demonstrated these distortion indices calculated from idealized tensor fields. It shows that 1) the four indices only depend on the orientations, not on the tensor or ODF shape; 2) splay, bend, twist indices provide complementary information about the orientational change, which demonstrate different types of orientational distortions.

We reconstruct fiber ODFs using NNSD\(^5\) from a single subject from Human Connectome Project (3 shells, 90 directions per shell, and \(b = 1000, 2000, 3000 \text{ s/mm}^2\) ). OO and OD were calculated from fODFs along their principal peaks. Fig. 3 demonstrated the fiber tracts cross a given ball ROI. The tracks were colored by using the proposed six scalar indices.

Conclusion
We proposed a unified framework called Director Field Analysis (DFA) to analyze a spherical function field and its extracted peaks. OO and OD are useful to describe the degree of alignment and dispersion of general spherical functions. The distortion indices demonstrated good sensitivity for the three different types of directional distortion in Fig.1, and have large values in areas with fiber curving and crossing.

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References
1. Andrienko, D., 2006. Introduction to liquid crystals. IMPRS school, BadMarienberg

Figures

Figure 1. Demonstration of three types of distortions.

Figure 2. Distortion indices calculated from different tensor fields. The tensors were visualized using superquadric tensor glyphs.
Figure 3. Fiber tracts cross a ROI colored by the six indices. The ROI is a crossing area of Corpus Callosum and Fornix, where all distortion indices have high values, especially for twist and total distortion indices.