DIFFUSION TENSOR IMAGING DATA WITH ULTIMATE INTERPOLATION WILL NOT SOLVE THE CROSSING-FIBER PROBLEM: A SIMULATION STUDY

K. Sakai[1], K. Yamada[2], K. Koyamada[1], T. Nishimura[2]

[1]CPEHE, Kyoto University, Kyoto, Kyoto, Japan, [2]Kyoto Prefectural University of Medicine, Kyoto, Kyoto, Japan

Introduction

Crossing-fiber problem [1] remains as one of the biggest unsolved issue on diffusion tensor imaging (DTI) based tractography. This problem can be characterized by the following two issues; (a) low fractional anisotropy (FA) voxel causing stopping and/or misdirection of tractography results and (b) undefined structural characteristics of fiber bundles (kissing, crossing, branching, or merging) within the voxel. The former issue (a) corresponds directly to the connectivity of tractography, which has been successfully solved by the TEND algorithm [2]. The latter issue (b) is directly related to the intra-voxel fiber orientation and the relative location of fiber bundles within the voxel. The tensor based algorithm has not yet reached a complete solution to this problem (b). One solution will be high angular resolution diffusion imaging (HARDI) [3]. Another possible solution may be higher resolution imaging using tensor based model. The objective of this paper is to assess whether we are able to solve the crossing fiber problem by higher resolution imaging achieved by tri-linear interpolation of neighbor tensor elements.

Table 1

No.	coordinate X	Y	Z	eigen value λ1	λ2	λ3	(	emax(x,y,z) x	y	z	)	FA
0	−1	−1	−1	2.4	1.0	1.0	(	1	1	1	)	0.839
1	0	−1	−1	2.4	1.0	1.0	(	0	1	1	)	0.839
2	1	−1	−1	2.4	1.0	1.0	(	−1	1	1	)	0.839
3	−1	0	−1	2.4	1.0	1.0	(	1	0	1	)	0.839
4	0	0	−1	2.4	1.0	1.0	(	0	0	1	)	0.839
5	1	0	−1	2.4	1.0	1.0	(	−1	0	1	)	0.839
6	−1	1	−1	2.4	1.0	1.0	(	1	−1	1	)	0.839
7	0	1	−1	2.4	1.0	1.0	(	0	−1	1	)	0.839
8	1	1	−1	2.4	1.0	1.0	(	−1	−1	1	)	0.839
9	−1	−1	0	2.4	1.0	1.0	(	1	1	0	)	0.839
10	0	−1	0	2.4	1.0	1.0	(	0	1	0	)	0.839
11	1	−1	0	2.4	1.0	1.0	(	−1	1	0	)	0.839
12	−1	0	0	2.4	1.0	1.0	(	1	0	0	)	0.839
13	0	0	0	1.0	1.0	1.0	(	0	0	0	)	0.000
14	1	0	0	2.4	1.0	1.0	(	−1	0	0	)	0.839
15	−1	1	0	2.4	1.0	1.0	(	1	−1	0	)	0.839
16	0	1	0	2.4	1.0	1.0	(	0	−1	0	)	0.839
17	1	1	0	2.4	1.0	1.0	(	−1	−1	0	)	0.839
18	−1	−1	1	2.4	1.0	1.0	(	1	1	−1	)	0.839
19	0	−1	1	2.4	1.0	1.0	(	0	1	−1	)	0.839
20	1	−1	1	2.4	1.0	1.0	(	−1	1	−1	)	0.839
21	−1	0	1	2.4	1.0	1.0	(	1	0	−1	)	0.839
22	0	0	1	2.4	1.0	1.0	(	0	0	−1	)	0.839
23	1	0	1	2.4	1.0	1.0	(	−1	0	−1	)	0.839
24	−1	1	1	2.4	1.0	1.0	(	1	−1	−1	)	0.839
25	0	1	1	2.4	1.0	1.0	(	0	−1	−1	)	0.839
26	1	1	1	2.4	1.0	1.0	(	−1	−1	−1	)	0.839

Methods

Table1 shows the property of utilized synthetic tensor field. The rectangular coordinates (X, Y, Z) and the origin O (No.13) are defined as shown in Table 1. The origin O is placed in the center of the cube composed by voxels. Each voxel is a cube with normalized edge length. The tensor in each voxel is modeled as being around the "crossing-fiber point". Table 1 also shows the eigen values, normalized eigen vector of the largest eigen value and FA value of each voxel. We used N^3 subdivided voxel (one edge divided by N) of synthetic tensor field to verify the distribution of degenerate area. We computed each subdivided tensor elements by using equation (1).

$$T = \sum_{i=1}^{8} \frac{T_i}{8}(1 - p_i p)(1 - q_i q)(1 - r_i r), \quad where \quad p_i = -1 or 1, \quad q_i = -1 or 1, \quad r_i = -1 or 1 \qquad (1)$$

In equation (1), T_i represents the tensor element at vertex position (p_i, q_i, r_i) and obtained by interpolation using normalized p_i, q_i, r_i with the conditions defined in equation (1). We employed the FACT algorithm [4] to depict the tractography.

Results

Figure 1 shows the results of the tractography. The color of tractography shows the intensity of the major eigen vector, which elevates from blue to red. Figure 1(A) shows tractography of the original data, in which the tractography stops at the boundary of the center voxel. Figure 1(B), (C) and (D) show the result of tractography from the interpolated voxels by dividing the original data into 512 sub-voxels (N=8). Figure 1(B) shows the tractography started from all vertices. Figure 1(C) shows the tractography starting from the rectangular box placed at the left hand side in the figure. In this figure, none of the tractography passed through the degenerate point. Figure 1(D) shows two streams of tractography starting from "start area-1" and "start area-2," respectively. These streams of tractography showed "kissing" situation but never had passed through the degenerate point. These tracts deflected to different direction before reaching the degenerate point.

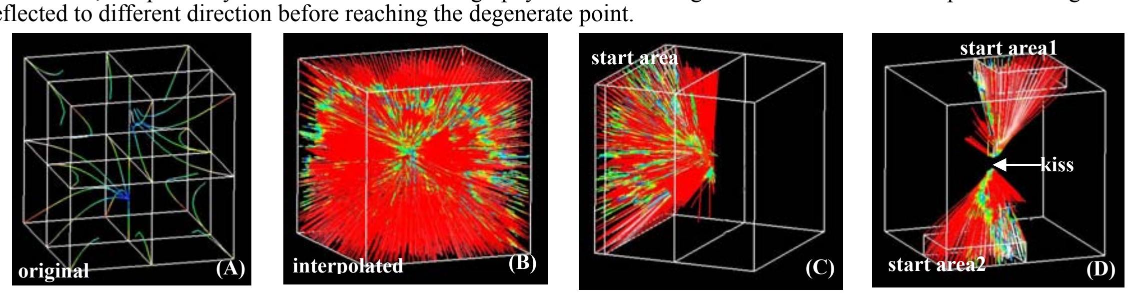

Figure 1

Discussion

The water diffusion characterized by tensor model causes diffusion degenerate points (low FA valued point) due to crossing fibers. At this diffusion degenerate point, tractography can result in stopping and/or misdirection. Thus the tensor model can not allow obtaining the suitable solution to the spatial orientation of intra-voxel fiber bundles. In this paper, we assessed the intra-voxel tensor distribution in the diffusion degenerate voxel by using tri-linear interpolation. This method can generate similar results to Euler and RK4 integration method when we employ extremely short step size.

We assumed the most restricted diffusion degenerate case for the assessment. In our model, the tracts converge to the canter of this field from eight different directions with same diffusion magnitude and the vector has no direction on the degenerate point. We believe that this model is very rare in the real life DTI, but suited to assess whether ultimately high spatial interpolation will be able to solve the crossing fiber problem. From the results, there were no tractography which passed through the degenerate point. When we employed more than 256 subdivided voxels (N=8) as shown in Figure 1, there were no changes in tractography patterns. As shown in Figure 1(B) and 1(C), most of all tractography constructed the kiss (close and away together) situation.

To generate situation such as crossing, branching and merging, we need artificial fiber tracing algorithm (e.g. TEND) which allows the tractography to pass through the degenerate tensor point. Artificial operation based on the certain mathematical model is needed to create the adaptive tractography around the tensor degenerate point. This is the limit of the degenerate voxel analysis based on the diffusion tensor model. The novel techniques based on new analytical methodology such as the HARDI and q-ball analysis will play an important role in depicting the intra-voxel fiber bundle structure.

Acknowledgements

This research was partially supported by the Japanese Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Young Scientists (B) 17700293.

References

[1] M. Kinoshita et al., *NeuroImage*, 25: 424-429(2005), [2] M. Lazar et al., *Human Brain Mapping* 18: 306-321(2003), [3] D. S. Tuch et al., *Magn Reson in Med* 48:577-582(2002), [4] S. Mori et al., *Annals of Neurology*, 45(2): 265-269(1999)