



## Comparison of three tracking methods of white matter fiber bundles based on diffusion MRI

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### ABSTRACT

Diffusion MRI is based on the measurement of Brownian motion of water molecules. It is possible to use this diffusion property as a probe to study the structure of spatial order in living brain tissues noninvasively. This paper put forward with a unified tracking algorithm based on diffusion tensor imaging, diffusion spectrum imaging and Q-Ball imaging. By applying the three methods to the same DWI dataset, different tracking results were got. The DTI tracking is fastest, and the number of fiber bundles is least; the DSI tracking is slowest, and the number of bundles is most; the QBI tracking is faster than DSI, but slower than DTI, and the number is larger than DTI, but smaller than DSI. DTI cannot track crossing bundles, but DSI and QBI can.

**Key words:** diffusion tensor, diffusion spectrum imaging, white matter, fiber bundle

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### INTRODUCTION

White matter is mainly composed of nerve fibers, and does not contain nerve cell bodies. It is the connection channel of central nervous system, lying in the interior of the brain. The tracking of fiber bundles is of great significance not only to cognitive research but also to clinical diagnosis. High-resolution imaging of brain tissue can be got by traditional MRI (example for T1, T2, and PD), but this can only reflect one aspect of physiological characteristics of brain organization. Diffusion MRI can characterize water anisotropic diffusion properties at each picture element (pixel) of an image. Diffusion MRI has developed rapidly from 1980s[1].

Diffusion MRI exploits self-diffusion of water molecules in brain tissue by applying diffusion sensitive magnetic field gradient on it. Because it can noninvasively track fiber bundle, Diffusion MRI has wide application in the brain diseases diagnosis and connected neural network research. Actually, the construction of white matter fiber bundles is very complicated, and there are crossing fiber bundles in some imaging voxels. The tracking of crossing fiber bundles needs high angle resolution.

DTI could only reflect the macro diffusion properties of water molecules in a voxel, and the tracking of crossing fiber bundles cannot be achieved by it. DSI needs to apply more sensitive magnetic gradients, and has high angel resolution. After dense enough q-space datasets are collected, displacement orientation distribution function is gotten through Fourier transform. But the number of datasets of DSI is from five to ten times larger than DTI. So this may affect its clinical application. Q-Ball imaging gets the orientation distribution function from q-space datasets by Funk-Radon transform.

Since diffusion MRI has the potential to the research on connection of neural networks, it has been greatly valued in recent years. This paper put forward with a new unified method to track WM fiber bundles based on the three diffusion MRI techniques. Compared with diffusion tensor imaging, DSI and QBI can provide more real information

on the physical structure of the fiber bundles. But the latter two need more magnetic gradients to collect enough q-space datasets, and are against their clinical practice because of their time-consuming procedure. Currently, diffusion MRI is the only noninvasive means of tracking three-dimensional white matter fiber bundles.

### DTI

DTI has developed rapidly in the last several years, and it is adapted to investigate anisotropic tissues (such as muscle fibers, white matter, etc.) by exploiting Brown motion of water molecules. DTI has been widely used in clinical diagnosis and brain function research.

Apparent diffusion coefficient (ADC) of DTI, macroscopically reflects the random motion trend (stochastic displacement) of all water molecules in a voxel. For anisotropic diffusion, tensor is needed to characterize diffusion coefficient. The coefficient implies the microstructure information of brain physiological tissue including tortuosity and ratio of extracellular space. In short, DTI reconstructs the images of brain tissues through measuring T2-weighted attenuated signal because of Brown motion of water molecules. According to Stejskal-Tanner equation (1), diffusion tensor  $D$  was calculated.

$$S_i = S_0 \exp(-b g_i^T D g_i) \quad i = 1, 2, \dots, 6 \quad (1)$$

where  $S_i$  is T2-weighted attenuated signal,  $S_0$  is original signal,  $b$  is diffusion factor,  $D$  is diffusion tensor,  $g_i$  is diffusion magnetic field gradient. The each side of equation (1) was applied by the logarithmic function, equation (2) was gotten. Because there are six unknown factors in ( $D$  is a symmetric positive definite 3x3 matrix), at least six magnetic field gradients must be applied in six different directions [2].

$$\ln(S_i) = \ln(S_0) - b g_i^T D g_i \quad (2)$$

Diffusion tensor usually is expressed as ellipsoid geometry, as shown in figure 1. There are three different types. First is long cylindrical, indicating that water molecules can only freely diffuse in a certain direction and cannot in others; Second is flat shape, indicating that water molecules can only freely diffuse in a certain plane; Third is spherical, indicating that water molecules can freely diffuse in all directions (isotropic diffusion) [3].

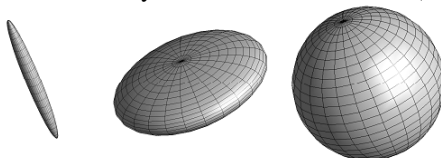


Fig. 1 Ellipsoids denoting three type diffusion tensors

### DSI

As a form of diffusion MRI, DSI is able to image living organ non-invasively by applying diffusion sensitive magnetic gradients. In q-space attenuated signals are collected, DSI images are gotten using Fourier transform. This imaging technique was invented by Wedeen in the year of 2000[4]. According the theory of Einstein, probability density function is used to describe the diffusion displacement. In 1991, Paul Callaghan proved that MRI signal can be calculated from q-space datasets using Fourier transform.

At present, DSI is a more complex kind of diffusion MRI imaging technique, and is able to provide most detailed anisotropic information of physical structure.

DTI cannot reflect the local maximum probability of anisotropic diffusion in a voxel. But DSI could describe multiply diffusion directions in a voxel by calculating the according local maximums of diffusion probability function. The contrast of DTI and DSI is shown as figure 2, (a)  $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$  are three eigenvectors of diffusion tensor; (b) the ellipsoid denoting diffusion tensor macroscopically reflects anisotropy; (c) diffusion probability density function, water molecules diffuse most easily in the direction of  $\lambda_1$  [5].

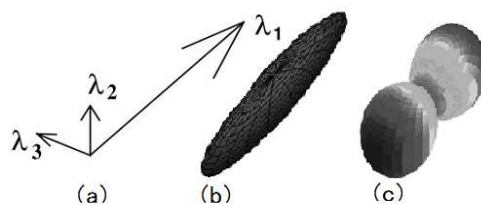


Fig. 2 The contrast of DTI and DSI, (a) three eigenvectors of DTI, (b) ellipsoid of DTI, (c) diffusion displacement probability of DSI

If  $S_{\Delta}$  is the attenuated signal and  $S_0$  is the signal without diffusion-sensitive magnetic gradients, the equation (1) is:

$$S_{\Delta} = S_0 \langle e^{i\mathbf{q}\cdot\mathbf{r}} \rangle \quad (1)$$

Where  $\langle \square \rangle$  is average operator,  $\Delta$  is diffusion time,  $\mathbf{r}$  is displacement vector,  $\mathbf{q} = \gamma\delta\mathbf{g}$  ( $\gamma$  is gyromagnetic ratio,  $\delta$  is the duration of magnetic gradient,  $\mathbf{g}$  is gradient vector) [6]. Because that the average of diffusion displacement of water molecules in a voxel equals to  $E(e^{i\mathbf{q}\cdot\mathbf{r}})$ , equation (2) was derived:

$$\begin{aligned} S_{\Delta} &= S_0 E(e^{i\mathbf{q}\cdot\mathbf{r}}) \\ &= S_0 \int_{R^3} p_{\Delta}(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}} d^3\mathbf{r} \end{aligned} \quad (2)$$

Where  $p_{\Delta}(\mathbf{r})$  is diffusion probability density function,  $R^3$  is the voxel space. From equation (2), we can infer equation (3):

$$p_{\Delta}(\mathbf{r}) = S_0^{-1} (2\pi)^{-3} \int_{R^3} S_{\Delta} e^{-i\mathbf{q}\cdot\mathbf{r}} d^3\mathbf{r} \quad (3)$$

Where  $p_{\Delta}(\mathbf{r})$  is called as diffusion spectrum function [7].

### QBI

The reconstruction method of QBI was proposed by Tuch, and it has two key parameters: the width of the Gaussian smoothing kernel, the width of the interpolation kernel. This method just need the sampling points on the sphere surface in q-space, and then QBI images are calculated through Funk-Radon transform [8]. But DSI must collect the all points in whole q-space in order to get diffusion images. Because the number of sample points of QBI is smaller than DSI, the reconstruction of QBI is time-saving. The radius of sphere could be selected randomly, and QBI need less strict configuration of magnetic gradients than DSI.

The mapping between Cartesian and spherical coordinates systems may introduce Cartesian artifacts in the ODF. Cartesian coloration of the ODF may be a particular problem at the coarse Cartesian resolution typically used for QSI. Further, the radial projection is highly inefficient since the projection discards a considerable fraction of the acquired data. The efficiency of QSI is also hampered by the strong pulsed field gradients needed to satisfy the Nyquist condition for the diffusion PDF in cerebral white matter. It is substantially more efficient to measure the diffusion ODF by directly sampling the diffusion signal on a spherical shell in diffusion reciprocal space [6].

The QBI reconstruction is based on the FRT, also known as the spherical Radon transform or simply the Funk transform.

To estimate the diffusion probability in a particular direction all that is needed is to sum the diffusion signal along the equator around that direction. This provides a model-free approach for estimating the diffusion probability from the spherically sampled diffusion signal. The exact relationship between the ODF and the FRT can be written as follows [9].

$$\varphi(\mathbf{u}) = 2\pi q' \int P(r, \theta, z) J_0(2\pi q' r) dr d\theta dz \quad (4)$$

Where  $J_0$  is the zeroth-order Bessel function,  $q'$  is the radius of the sampling shell and  $Z$  is a normalization

constant.

### Unified tracking algorithm

This paper proposed a unified tracking algorithm based on diffusion MRI including DTI, DSI, and QBI. The process is as follow:

1)Reconstruct DTI/DSI/QBI images;

2)As to DTI, we calculated the principal eigenvectors of each voxel. As to DSI, we calculated the local maximums of diffusion probability density function. As to QBI, we calculated the local maximums of orientation distribution function;

3)Setup the tracking parameters of step size, angle(equation 5), and length(equation 6) of fiber bundle;

$$\theta = \arccos \frac{\mathbf{v}_1 \cdot \mathbf{v}_2}{|\mathbf{v}_1| \cdot |\mathbf{v}_2|} \quad (5)$$

$$L_{\min} \leq L \leq L_{\max} \quad (6)$$

4)Select ROIs, then find the smooth curves among all diffusion directions according to the local maximums.

As shown in figure 3, the tracking of single fiber bundle and of crossing fiber bundle was described: (a) the tracking based on DTI, (b)the tracking based on DSI. One DTI voxel has only one diffusion vector, and one DSI voxel may have several diffusion vectors. The dark blue line denotes a tracking line, and the red line denotes another crossing tracking line.

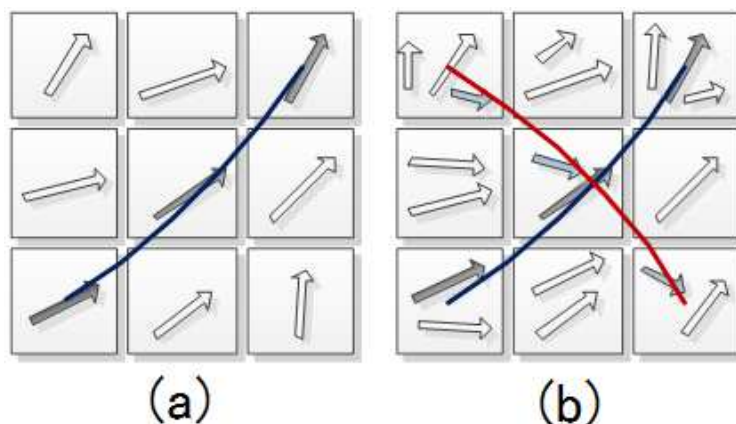


Figure 3 Tracking of nerve fiber bundles, (a) Tracking based on DTI, (B) Tracking of crossing fiber bundles based on DSI and QBI

## RESULTS

Tracking results of nerve fiber bundles within the entire brain region is shown as figure 4. The first low is the result of DTI, the middle low is of DSI, and the third one is of QBI. From the tracking results, we can get the conclusion that the method based on DTI cannot track crossing fiber bundles, but the method based on DSI or QBI can.

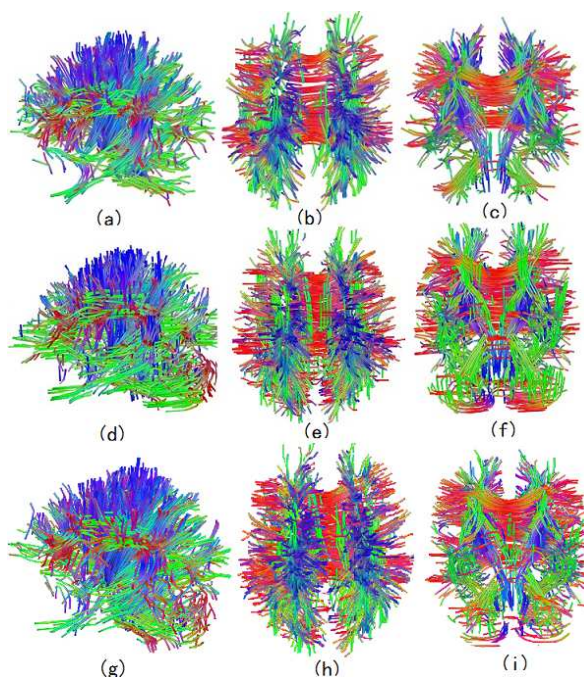


Figure 4 Tracking results within whole brain region, the first low is of DTI, the middle one is of DSI, The third one is of QBI

The first column is of sagittal view, the middle one is of coronal view, the third one is of axial view.

Corpus callosum locates at the bottom of the two spheres, which is the largest commissural fiber bundles. The fiber crosses the midline, and goes into the gyri forming the radiation of connection.

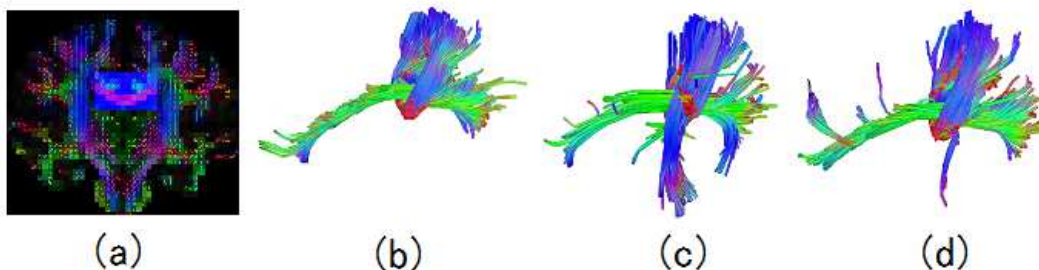


Figure 5 Tracking results of corpus callosum fiber bundles, (a)ROI, (b)DTI, (c)DSI, (d)QBI

The ROI is shown as figure 5, including the constructions of corpus callosum, thalamus, and medulla.

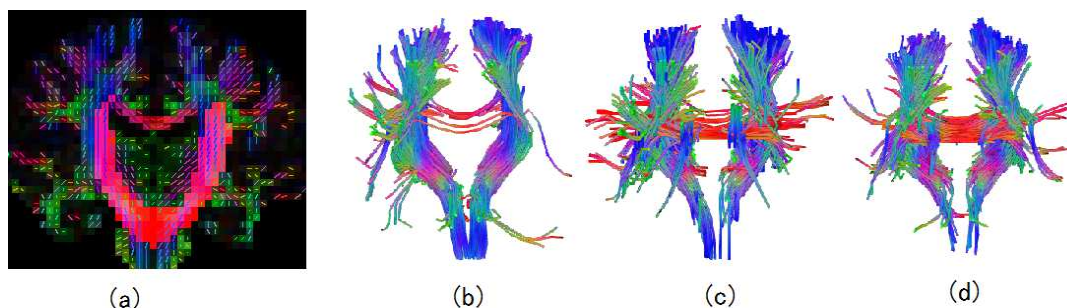


Figure 5 Tracking results of the local region fiber bundles, (a)ROI, (b)DTI, (c)DSI, (d)QBI

## CONCLUSION

MRI tractography is the mapping of neural fiber pathways based on diffusion MRI of tissue diffusion anisotropy. This paper proposed a unified method to track fiber bundles and compared with each other. Tractography based on diffusion tensor imaging (DTI) cannot directly image multiple fiber orientations within a single voxel. In contrast, none of these examples of fiber crossing and complex structure was identified by DTI analysis of the same data sets. These findings indicate that DSI/QBI tractography is able to image crossing fibers in neural tissue, an essential step

toward noninvasive imaging of connectional neuroanatomy.

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