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DTI fiber tractography of human brain

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Abstract. DTI fiber tractography is a powerful tool for investigating the human brain's structural connectivity. It enables us to explore the complex network of fiber pathways that connect different regions of the brain and play a crucial role in its function. In this work, I used DWI(Diffusion-Weighted Imaging) data processing software (such as DiffusionToolkit, and Trackvis) to construct fiber tracks of the human brain based on MRI(Magnetic Resonance Imaging) data and investigated the brain anatomical structure of a human subject using DTI(Diffusion tensor imaging) fiber tractography. The two software I used was Diffusion Toolkit and Trackvis. Diffusion Toolkit did the preparation work for Trackvis, including data reconstruction and fiber tracking on diffusion-weighted MR(Magnetic Resonance) images. Trackvis was utilized for the tractogram visualization and further analyses of the white matter tracts generated by using DTI fiber tractography. In this work, I successfully used Diffusion Toolkit and Trackvis to construct fiber tracks of the human brain, and the results were correct when compared to the standard brain. Besides, I summarized the principle of DTI and the advantages and disadvantages of the technology.

Keywords: magnetic resonance imaging, diffusion-weighted imaging, diffusion tensor imaging, tractography reconstruction.

1. Introduction

DTI (Diffusion tensor imaging) is a new magnetic resonance imaging technique developed based on DWI (Diffusion-Weighted Imaging). DTI is based on the movement direction of water molecules. It uses diffusion MRI to estimate the diffusion tensor at each voxel in the brain that noninvasively shows the direction of white matter fibers in the brain [1]. Here is the principle of DTI.

1.1. Diffusion

The first formal description of diffusion was made in 1827 by Robert Brown, a Scottish botanist [2]. Diffusion refers to the movement of material molecules from areas of high concentration to areas of low concentration until they are evenly distributed. For example, when ink is introduced into water, the ink particles are subject to the chaotic movements of water molecules, leading to a random dispersion in various directions until the water in the container is uniformly colored.

The speed of diffusion is influenced by the properties of the medium like temperature and viscosity of the medium [3]. Besides, the size and shape of the container are also factors that affect the rate of diffusion. For example, if ink is added to a beaker, it will rapidly spread throughout the volume of the beaker, causing the ink particles to encounter the container walls, thereby compelling them to move in

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an upward or downward direction. It means that the container's dimensions cause the particles to diffuse along a predominant axis.

1.2. b-values and b-vectors

The equation of b-value is $b = \gamma^2 G^2 \delta^2 (\Delta - \delta/3)$, G is the magnitude of diffusion gradient, Δ is the time between gradients, and δ is the T duration of the diffusion gradient. The b-value is proportional to the magnitude of the gradient, duration of the gradient, and time between the gradients.

The contrast of diffusion-weighted images is impacted by the b-values [4]. By using a b-value of zero, a diffusion-weighted image appears similar to a standard T2-weighted image, where grey matter appears bright and white matter appears dark. As shown in Fig.1, when the b-value increases, there is a greater signal loss in specific parts of the brain, primarily within the white matter [5]. The cause for the signal loss in white matter tracts is that water diffusion primarily occurs along the tract direction, resulting in a lower signal intensity in the generated image.

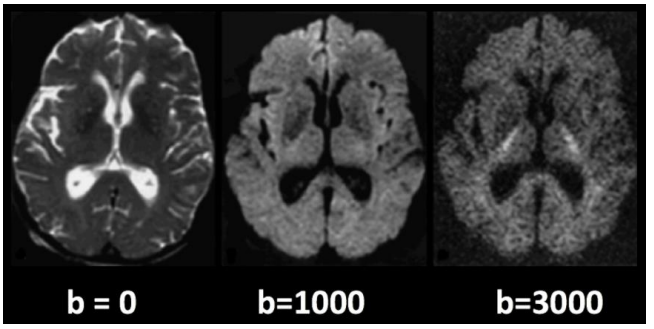

Figure 1. The diffusion-weighted images of different b-values.

The b-vectors specify the diffusion gradient's orientation in the x, y, and z directions for a given volume. In addition, by utilizing the b-values and b-vectors together, we can create a tensor and apply it to every voxel of the diffusion-weighted image. The tensor can be viewed as a representation of forces exerted in the x, y, and z directions, while each voxel is a composition of eigenvalues and eigenvectors. The eigenvectors signify the direction of diffusion, whereas the eigenvalues correspond to the diffusion magnitude.

1.3. Fractional Anisotropy (FA)

The equation of FA(Fractional Anisotropy) is $FA = \sqrt{\frac{3((\lambda_1-\bar{\lambda})^2+(\lambda_2-\bar{\lambda})^2+(\lambda_3-\bar{\lambda})^2)}{2({\lambda_1}^2+{\lambda_2}^2+{\lambda_3}^2)}}$, and λ_1, λ_2, λ_3 are eigenvalues.

FA is a parameter of the anisotropy, and the value is between zero and one. A higher fractional anisotropy (FA) value suggests that diffusion is more aligned in a specific direction, whereas a lower FA value suggests that diffusion may either be highly isotropic with random directionality, or diffusion may be severely restricted [6].

2. Methods

The two software used in the project is Diffusion Toolkit and Trackvis. Diffusion Toolkit did the preparation work for Trackvis, including data reconstruction and fiber tracking on diffusion-weighted MR images. Data reconstruction refers to generating the files needed in the process of DTI fiber tractography, such as the density and distribution orientation of white matter fiber bundles. In addition, Diffusion toolkit could do fiber reconstruction and tractography, and in this project, deterministic fiber bundle tracking was conducted using it. Trackvis was utilized for the tractogram visualization and further analyses of the white matter tracts generated by using DTI fiber tractography.

Fig.2 shows the interface of Diffusion Toolkit. First, DTI was chosen as the imaging model, and then the "All_DWI.nii" file, which is the raw data file used for reconstruction, was imported. The b-value

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was set to be 1000, the number of b_0 to be 3, and the gradient table to be 30 gradient directions, based on the DWI data information. Additionally, the feature vector which was shared with me was changed. Various permutations regarding the image orientation information were conducted to determine the proper orientation, and it was found that "(1,0,0), (0,1,0)" was the correct orientation. In this case, if the image orientation info is changed, the fiber track image would turn yellow, indicating signal dropout and image blurring. For example, changing "(1,0,0),(0,1,0)" to "(1,0,0),(0,0,0)" would result in a two-dimensional image.

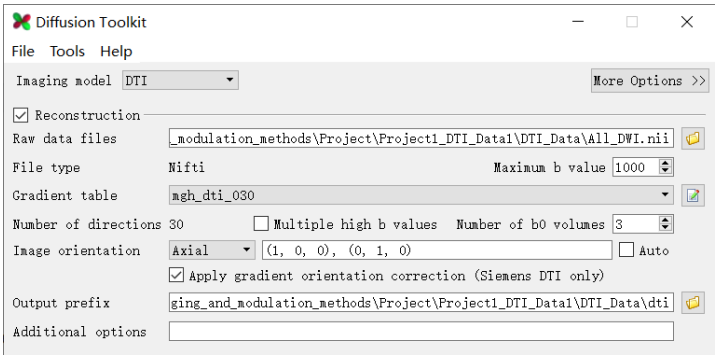

Figure 2. Data parameter setting in diffusion toolkit.

After running Diffusion Toolkit, Trackvis was launched and the tracking file “dti.trk” was opened. Meanwhile, the image of fiber tracts within a human brain could be observed. In the work, the "dit_dwi.nii" file was uploaded to overlay the fiber tracts on the DWI image for improved displays, as shown in Fig.3.

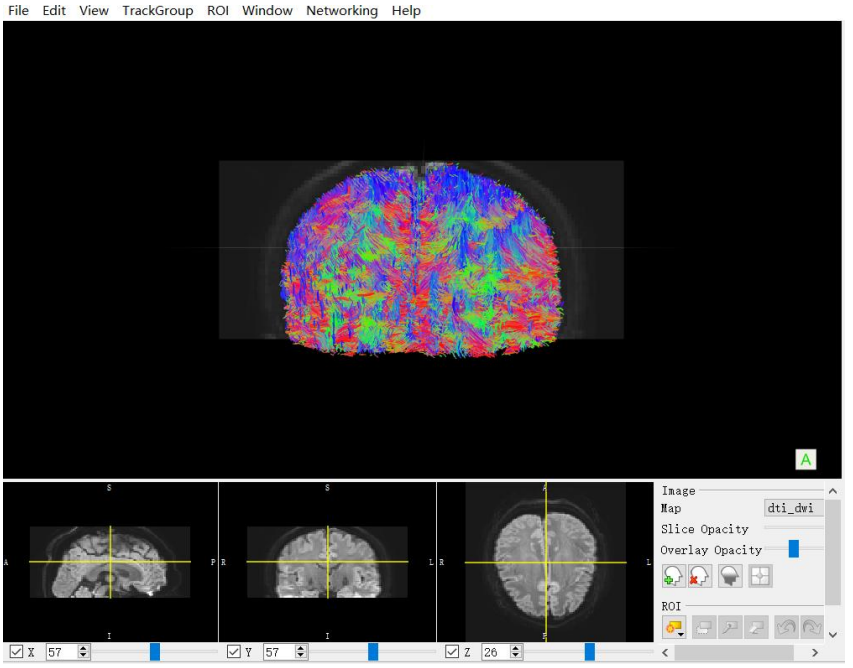

Figure 3. Fiber tracts image and DWI image showed in Trackvis.

The fiber bundle length was adjusted to an appropriate value, and filtering was performed to visualize the fiber tracts in specific areas of the brain, such as using the y slice filter to show the tracts across the Y-axis plane, as depicted in Fig.4.

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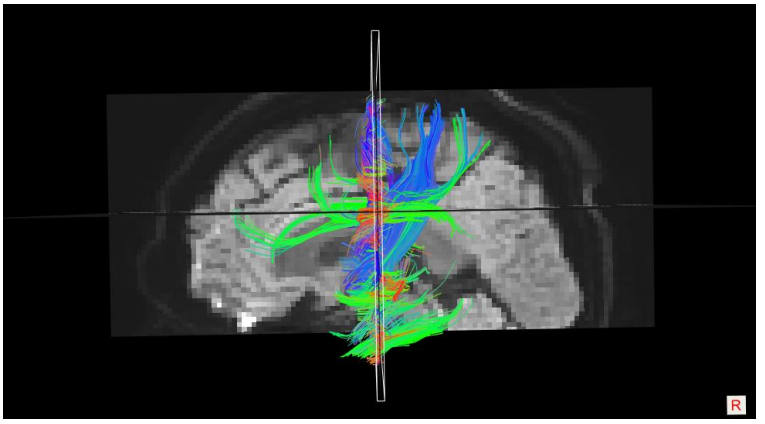

Figure 4. Fiber tracts across the specific Y-axis plane.

2.1. Verification

The corpus callosum is an arcuated plate of fibers connecting the left and right hemispheres of the brain on the midsagittal section of the brain. It is the largest white matter structure in the brain. By setting the corpus callosum as ROI(Region of interest), the corpus callosum in the generated fiber tracking image can be compared with that in the standard brain, to determine whether the results are correct. Fig.5 shows Color FA map of the human brain generated by Diffusion Toolkit.

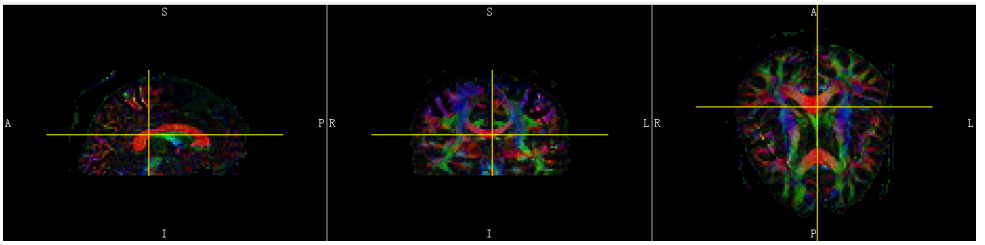

Figure 5. Color fa map of the brain generated by diffusion toolkit.

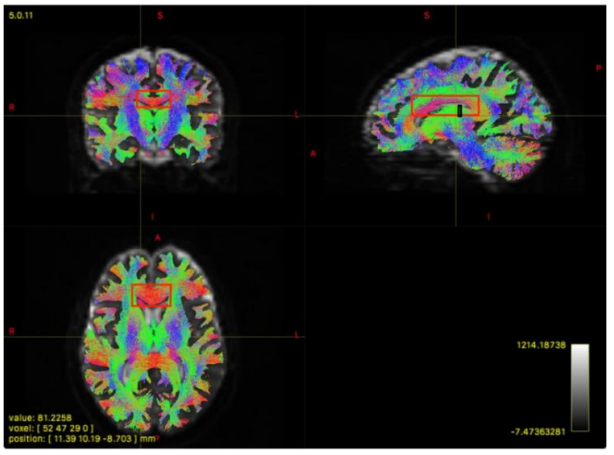

Figure 6. Streamline distribution of standard brain.

In Fig.6, the structure circled in red is the corpus callosum. In the streamlined distribution map, red, green and blue represent left-right, anterior-posterior and superior-inferior orientation, respectively. So according to the image of the standard brain, the fibers of the corpus callosum are oriented left and right in the standard brain. By comparing the color and morphology of the corpus callosum with the Color FA map created using Diffusion Toolkit, the correctness of the conclusion can be verified.

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To further verify the correctness of the results, the fibers from other regions of interest (ROIs) can be compared with those of standard brains. The ROI was set in the occipital lobe region on Trackvis, and the fiber tracking image in Fig.7 can be observed for further comparison of the fibers with standard brains. At this point, the coordinates of ROI and its position in the FA image are also shown in Fig.7.

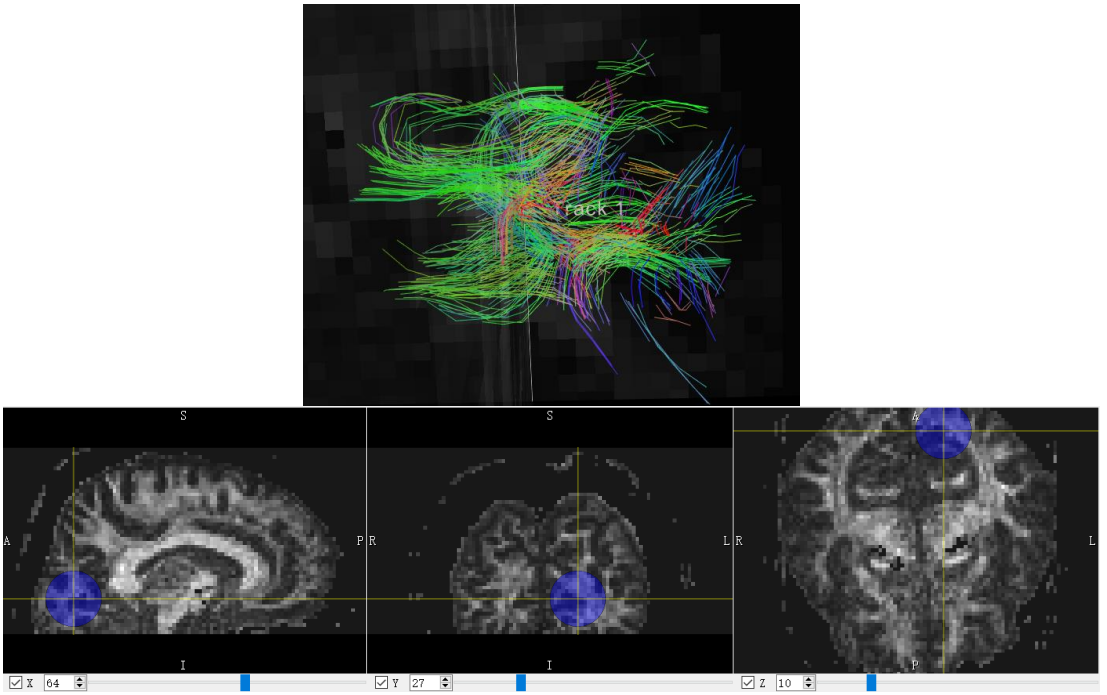

Figure 7. Fiber tracking of the occipital lobe, and the coordinates of ROI at this point.

Streamline results generated by probabilistic fiber bundle tracking of the left hemisphere occipital cortex are shown in Fig.8. The probabilistic fiber bundle tracking is generated as follows: 2000w Streamline is generated in the whole brain, and MRtrix is used to randomly intercept 20w of them, and map them to T1 structure image to show the results.

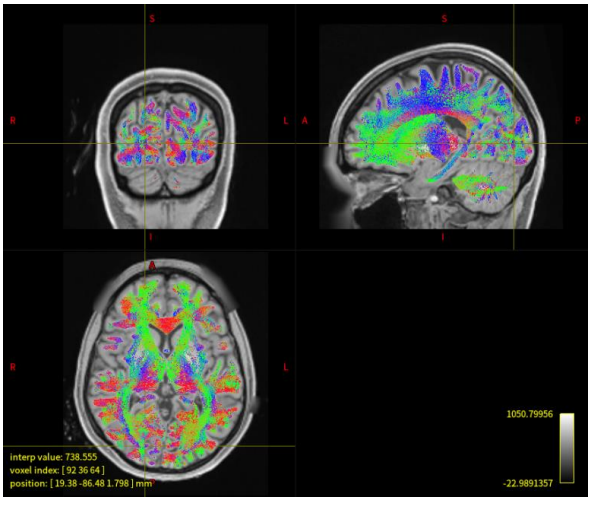

Figure 8. Three views of the left hemisphere occipital cortex (streamline results generated by probabilistic fiber bundle tracking).

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Next, the image of the left hemisphere occipital lobe was enlarged in three views, as shown in Fig.9. The correctness of the results of DTI fiber tractography could be verified by comparing them with the image of fiber tracking of the occipital lobe generated with Diffusion Toolkit in Fig.7.

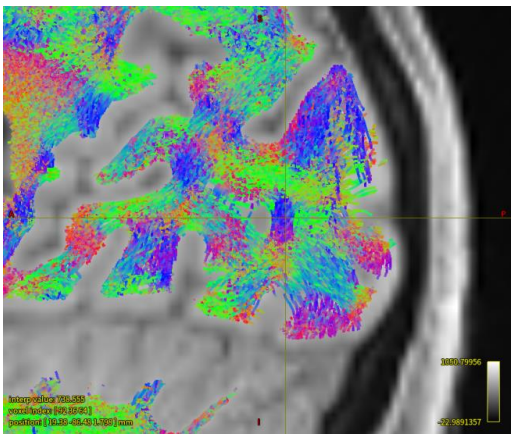

Figure 9. Streamline results of probabilistic fiber bundle tracking of occipital lobe.

3. Results

Fiber tracks of the human brain were successfully constructed with Diffusion Toolkit and Trackvis.

First, in Fig.5, the Color FA map I created with the Diffusion Toolkit was compared with the image of the standard brain in Fig.6. It was observed that the position of the corpus callosum in the image was also red (left and right orientation), and its status was similar to that of the standard brain.

Second, the image of fiber tracking of the occipital lobe generated with Diffusion Toolkit in Fig.7 was compared with three views of the left hemisphere occipital cortex in Fig.8, and it was observed that the general direction of nerves in the occipital lobe was similar.

After comparing fibers in RoIs of the corpus callosum and the occipital lobe with the standard brain, it can be verified that the results of DTI fiber tractography are correct.

4. Discussion

4.1. Pros of DTI

DTI fiber tracking is a valuable technique in neuroimaging research and clinical practice for understanding the structural connectivity of the brain [7]. The technique uses a variety of parameters and data processing. The variation of diffusion can be reflected in the form of a vector, which can reflect the anisotropy of white matter. In addition, DTI images can be displayed by feature vector maps through post-processing software, providing information on the structural connections between different brain regions, which is of great help to the study of white matter.

DTI fiber tracking has been used in a variety of applications, including identifying structural changes in neurological disorders such as Alzheimer's disease and multiple sclerosis, mapping the structural connectivity of the developing brain, and planning surgical interventions. For example, DTI can reveal how brain tumors affect nerve cell connections and help doctors in brain surgery.

4.2. Cons of DTI

However, it's important to note that DTI fiber tracking has some limitations and potential sources of error.

First, the lack of preprocessing function in Diffusion Toolkit and the use of data files without preprocessing in this project may have an impact on the quantitative analysis of DTI. Besides, the accuracy of DTI is also affected by the late image processing algorithm, such as the choice of fiber tracking algorithm, and the specific parameters chosen for the algorithm, which makes the processing result uncertain [8].

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Second, the Crossing-Fibers Problem has impeded the efficacy of DTI, as fiber tracking inaccuracies are commonly encountered in regions where fibers cross. The root of this issue is the tensor fitting methodology, which is suited for examining voxels that only contain unidirectional white matter tracts. However, when fibers cross within a voxel, the tensor method may produce unreliable outcomes as it is compelled to provide a singular solution to estimate all the eigenvalues and eigenvectors. The tensor technique is incapable of determining the direction and intensity of diffusion for each fiber bundle separately [9].

Spherical Deconvolution is a technique that was developed to tackle the Crossing-Fibers Problem [10]. It is used in the software package MRtrix. Unlike the conventional method of obtaining a solitary solution for each voxel's intricate signal, Spherical Deconvolution postulates that the diffused signal is the mean of what one would anticipate from numerous individual fibers intersecting at varying angles. Thus, in Spherical Deconvolution, more intricate signals are deconvolved using individual fibers as a basis function.

5. Conclusions

DTI fiber tractography is a valuable tool in neuroimaging research and clinical medical practice, but it should be used in appropriate situations with careful consideration of its limitations and potential sources of error to avoid irreversible effects on research or medical diagnosis.

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