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DTI Tractography

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Abstract. The DTI technology used to observe the Nerve fascicle - "Nerve fascicle imaging" was also discussed in detail. Two types of deterministic and probabilistic traction imaging were compared from effectiveness and computational efficiency perspectives. Then an experimental study was conducted using different software to compare the fiber bundles of the subject's brain and the normal brain and to evaluate the impact of different angle thresholds on the number of observable fiber bundles. Research has confirmed that the subjects' whole brain fiber bundle imaging reconstruction was successful, and there was no significant difference compared to the normal brain fiber bundle. The study also found a specific quantitative relationship between the angle threshold and the number of fiber bundles. This experiment also explored the differences in connectivity strength between the brain regions of the left and right brains and their significance.

Keywords: DWI, DTI, Tractography, Brain connectivity strength.

1. Introduction

1.1. DWI

Diffusion-weighted imaging (DWI) is very common in the medical field and is usually used in the imaging science of radiology. This technique is primarily used in magnetic resonance imaging (MRI) scans [1].

The imaging principle of DWI is based on Brownian motion. Brownian motion refers to the random movement of water molecules. In biological tissues, water molecules are constantly in motion because of the presence of thermal energy. However, it is worth noting that the movement of water molecules is also subject to conditions, such as cellular structures, cell membranes, and other cellular components that impede their movement.

DWI takes advantage of this phenomenon and utilizes the special gradient, which measures how fast water molecules diffuse in different directions within the cellular tissue. If it's in an area where water diffusion is unrestricted, there's a relatively high magnetic resonance imaging signal. Conversely, the MRI signal is reduced when the water diffusion is impeded or restricted.

On the practical side, the DWI scan will consist of several images acquired with different gradient intensities (called b-values). the higher the b-value, the more diffusion-weighted the image. By analyzing the signal intensity of these images, the clinician can generate maps showing water's apparent diffusion coefficient (ADC) in different tissues. The rate and direction of water diffusion can be

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demonstrated in an ADC map, which can provide a lot of information about the microstructure of a tissue.

1.2. DTI

1.2.1. What is DTI, the relationship between DWI and DTI. DTI is an extension of the DWI technique to obtain more information about the diffusion of water molecules within a tissue. The formation of DTI is achieved by acquiring many images of DWI and applying diffusion gradients in different non-collinear directions. Once these images are captured, the diffusion tensor can be calculated. This is a mathematical model that describes the 3D diffusion behavior of water in each voxel (3D pixel) in a tissue.

The diffusion tensor in DTI represents the magnitude and direction of water diffusion along the three principal axes.

In essence, DTI implements a more advanced and informative technique based on DWI, which can play a major role in the study of tissue microstructure and the organization of brain white matter bundles. Therefore, it has a unique value in the field of neuroscience. The main purpose is to observe the fiber bundles and to provide help for making surgical plans before surgery and evaluating brain function after surgery.

1.2.2. Fractional anisotropy (FA). Fractional anisotropy (FA) is a common quantitative parameter in diffusion tensor imaging (DTI), a special form of magnetic resonance imaging. FA measures the degree of anisotropy, or directionality, of the diffusion of water in a voxel (three-dimensional pixel) within a tissue.

For example, in white matter fiber tracts in the brain, which are well organized, water diffusion tends to be more directional or anisotropic along the length of the fiber. Conversely, if regions are less organized or have more anisotropic diffusion, such as the cerebrospinal fluid (CSF), the directionality of water diffusion is less dominant [2].

The FA value will vary from 0 to 1. When FA is 0, this indicates isotropic diffusion, which means that the water molecules diffuse equally in all directions; if it is 1, then the water molecules are moving primarily in one direction.

$$FA = \sqrt{\frac{(\lambda_1-\lambda_2)^2+(\lambda_2-\lambda_3)^2+(\lambda_1-\lambda_3)^2}{2(\lambda_1{}^2+\lambda_2{}^2+\lambda_3{}^2)}}$$

Figure 1. The formula for FA.

1.3. Tractography

Tractography is a technique in diffusion tensor imaging (DTI) used to visualize nerve bundles or pathways in the brain. It uses the principle that water in the brain's white matter fibers tends to diffuse in the direction of the fibers rather than perpendicular to them to generate images of the fiber pathways in the brain.

It will be color-coded according to the orientation of the fiber bundles (e.g., fibers going from left to right will be colored red, fibers going from front to back will be colored green, and fibers going from top to bottom will be colored blue) and can be analyzed in three-dimensional visualization.

It is divided into two main types: deterministic fiber bundle tracking and probabilistic fiber bundle tracking.

Deterministic fiber bundle tracking: This method assumes that the primary diffusion direction of each voxel (the smallest box-shaped part that can be distinguished in the 3D image) represents the direction of a single fiber bundle. It creates a fiber bundle by moving from voxel to voxel in this direction. This method is straightforward and computationally efficient but is not as powerful in regions where fiber bundles cross, bend sharply, or diverge [3].

Probabilistic fiber bundle tracking: This method measures and diffuses the uncertainty in the direction. Instead of assuming a single direction, it creates a distribution of possible directions on each

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voxel and generates many potential paths. This approach better handles regions where fibers cross or diverge, providing a more robust characterization of complex brain connections. But it requires a lot of computation, so it can be time-consuming [3].

Fiber bundle imaging can be very helpful in neurosurgical planning, allowing surgeons to avoid damaging important fiber bundles. It can also be used to study diseases affecting the white matter of the brain, such as multiple sclerosis, and to investigate the brain's connectivity [4].

1.4. The strength of structural connections in the brain

The strength of structural connections in the brain refers to the strength of connections between fiber bundles in different brain regions, mainly related to the density of fiber bundles. Different connection strengths may be related to brain functions such as memory and cognitive learning. Because DTI can measure the diffusion direction of water molecules in nerve fiber bundles, it can reveal the direction and connectivity of white matter fibers, thereby inferring the strength of structural connections between brain regions.

1.5. Objective

Magnetic resonance imaging (MRI) has been a cornerstone in the field of neuroimaging, providing a noninvasive way to observe and understand the internal structures of the human brain. With the advent of advanced techniques such as diffusion-weighted imaging (DWI) and diffusion tensor imaging (DTI), the insights that MRI can provide have been greatly enriched, especially when studying the brain's white matter.

The potential application areas for these technologies are vast. From assisting in neurosurgical planning and understanding developmental changes in the brain to studying the complex network of connections in the brain called the connectome to detecting and monitoring diseases affecting the brain's white matter, DWI and DTI are becoming essential tools in neuroscience.

However, they have several unsolved questions and limitations:

1. Resolution Limitation: DWI and DTI can't resolve complex fiber configurations like crossing, kissing, or diverging fibers. In regions with complex fiber orientations, tractography can produce erroneous results.

2. Assumption of Gaussian Diffusion: DTI assumes that the diffusion of water molecules in the brain tissue is Gaussian. However, this isn't the case in areas with complex fiber arrangements.

3. Length and Density of Tracks: Determining the true length and density of the tracts is still a challenge. The generated tracks might not necessarily represent the actual neural pathways.

4. Biological Interpretation: It's difficult to infer specific biological information from the diffusion signals. For example, tractography can't differentiate between afferent and efferent fibers.

5. False Positives and Negatives: There's a risk of generating false-positive tracts (tracts that don't exist) or missing real tracts (false negatives).

6. Parameter Selection: The choice of parameters, such as the fractional anisotropy (FA) threshold or the angle threshold, can greatly influence tractography outcomes. There's no universally accepted standard for these parameters.

7. Tissue-Specific Limitations: Certain brain tissues, like the gray matter, don't provide reliable DTI data.

8. Motion and Distortion: Patient movement or inherent MRI-related distortions can affect the quality and accuracy of DWI and DTI data.

9. Lack of Ground Truth: There's no gold standard for validating

As our understanding of the brain has deepened, the methods used to study it have become more complex and specific. By scanning sample data, this paper verified the accuracy of the fiber beam tracking results, and in the follow-up experiment, more data were used to study the laterality of the brain and explore some brain regions with significant differences in the whole brain. The aim is to clarify the working principle, advantages, challenges**,** and future prospects of DWI, DTI**,** and beam imaging through an in-depth study of the principles of DWI, DTI**,** and beam imaging.

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2. Method

2.1. Comparison of fiber bundles between the subject brain and normal brain

Open the Diffusion Toolkit and select DTI from the Imaging model. During Reconstruction, set the b value to 1000, select Axial from Image orientation, and set it to (1,0,0), (0,1,0). Set the Angle value to 35 in the Tracking step, and then import the subject's DWI data. When everything is set up, click the "run" button, and we will see the Trackvis software open, and a whole brain fiber made of multi-colored fibers is presented.

Then, three methods were adopted to extract the desired fiber bundle.

In the first method, a Sphere is created, and then by adjusting the values of the x,y, and z axes in the ROI, some concentrated and tightly colored fiber bundles are presented, which are part of the fiber bundles of certain brain regions.

In the second method, by setting a Length threshold in the ROI, some fiber bundles that are too long or too short are removed. This process is mainly to remove the surrounding chaotic fiber bundles so that the fiber bundles in a certain brain area can be clearly displayed. Then, rotate the x,y, and z axes to find the brain region being studied.

In the third approach, 3D Slicer software is used. After the fiber bundle is extracted with a 3D Slicer, three planes are drawn horizontally on the fiber bundle to reduce the scope of its presentation so as to obtain a suitable range of fiber bundle (this range can be arbitrarily specified).

Next, for the first and second methods, the MRtrix software was used. By importing DWI data(Which is a normal subject from the HCP data [5], generated through probabilistic fiber bundle tracking, and has been registered in the MNI standard space) from the normal human brain, a three-view of the normal human brain fiber bundle can be obtained, which is used to compare with the fiber bundle of the subjects' human brain obtained above. Because the two-three views obtained in Trackvis and MRtrix are not in the same space, the position of the fiber bundle cannot be determined by directly substituting the data of the x,y, and z axes, but the approximate position of the fiber bundle can only be determined by comparing the three views presented in the two software.

2.2. Variation of the number of fiber bundles at different angle threshold

By setting different Angle thresholds in the Diffusion Toolkit, the corresponding number of different human brain fiber bundles can be obtained. Because the minimum angle that can be set is 5 degrees and the maximum angle is 90 degrees, this experiment adopts the method of starting from 5 degrees and recording data every 5 degrees until 90 degrees. Their quantitative relationship is plotted as a linear graph. In this experiment, the linear relationship between the angle threshold and the number of fiber bundles was plotted at 3mm and 6mm, respectively.

2.3. Strength of the connections between the left and right brain

The brain structural connectivity strength data of 45 subjects were obtained from HCP [5]. Standardize data by writing a Python program. [7][8]A t-test was conducted on the data of 45 participants with different connectivity strengths between specific brain regions in the left and right hemispheres to obtain p-values.

A p-value less than 0.05 indicates significant results, with significance thresholds including 0.05, 0.01, 0.005, 0.001, and a smaller value indicating greater significance.

3. Result

3.1. Comparison of fiber bundles between the subject brain and normal brain

After adjusting a series of parameters on Trackvis, a brain-wide image of the fiber bundles was obtained (As shown in Figure 2).

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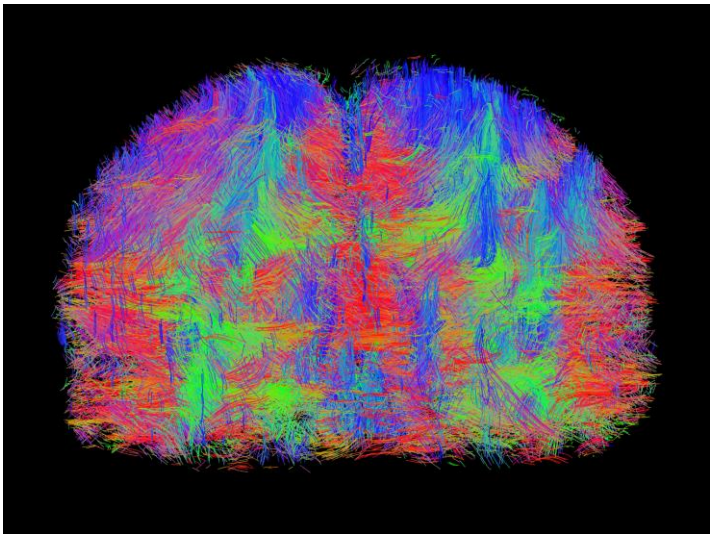
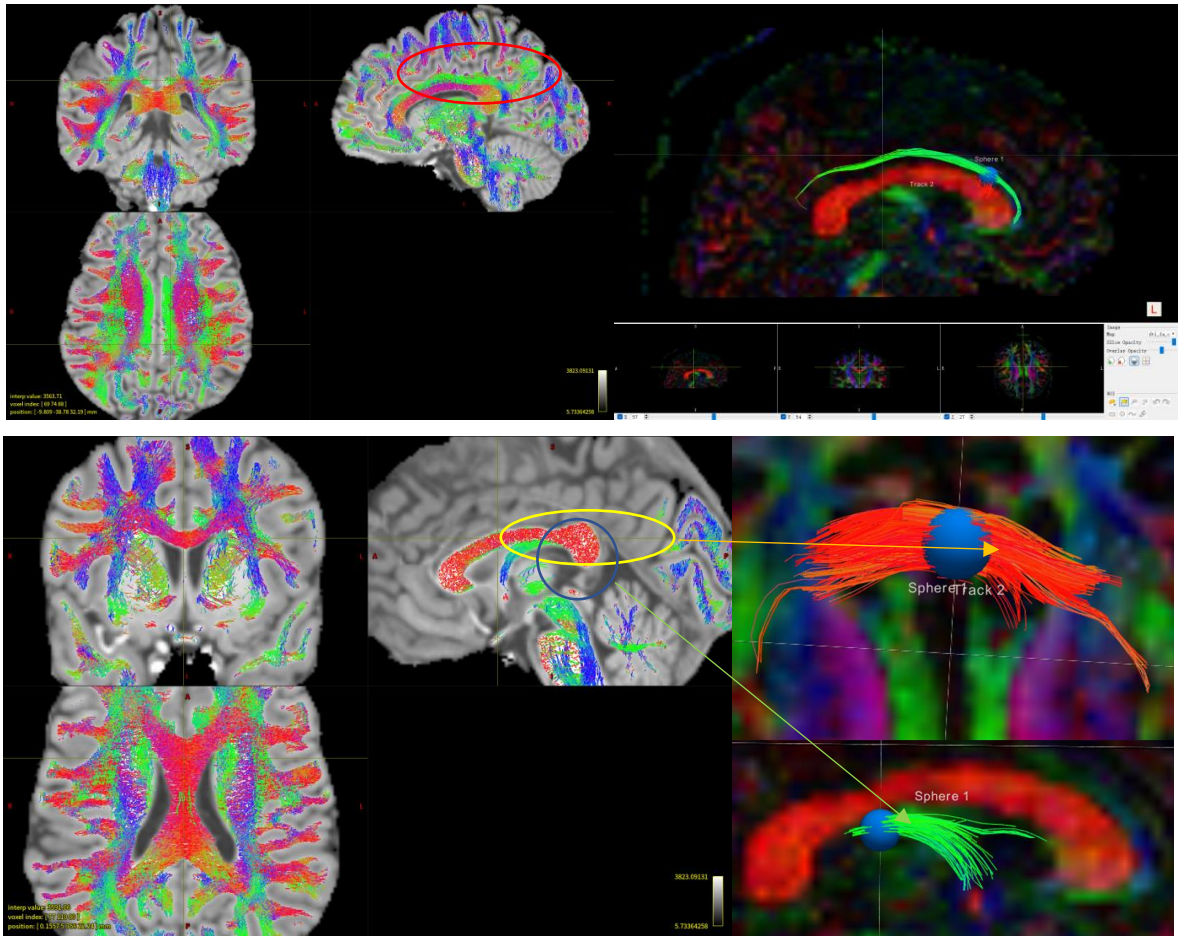


Figure 2. Whole brain fiber bundle imaging image.

As you can see, the fiber bundles obtained by the first method(As shown in Figure 3) and the second method(As shown in Figure 4) are compared to the three views obtained in MRtrix, and the result is that the fiber bundles are very similar.



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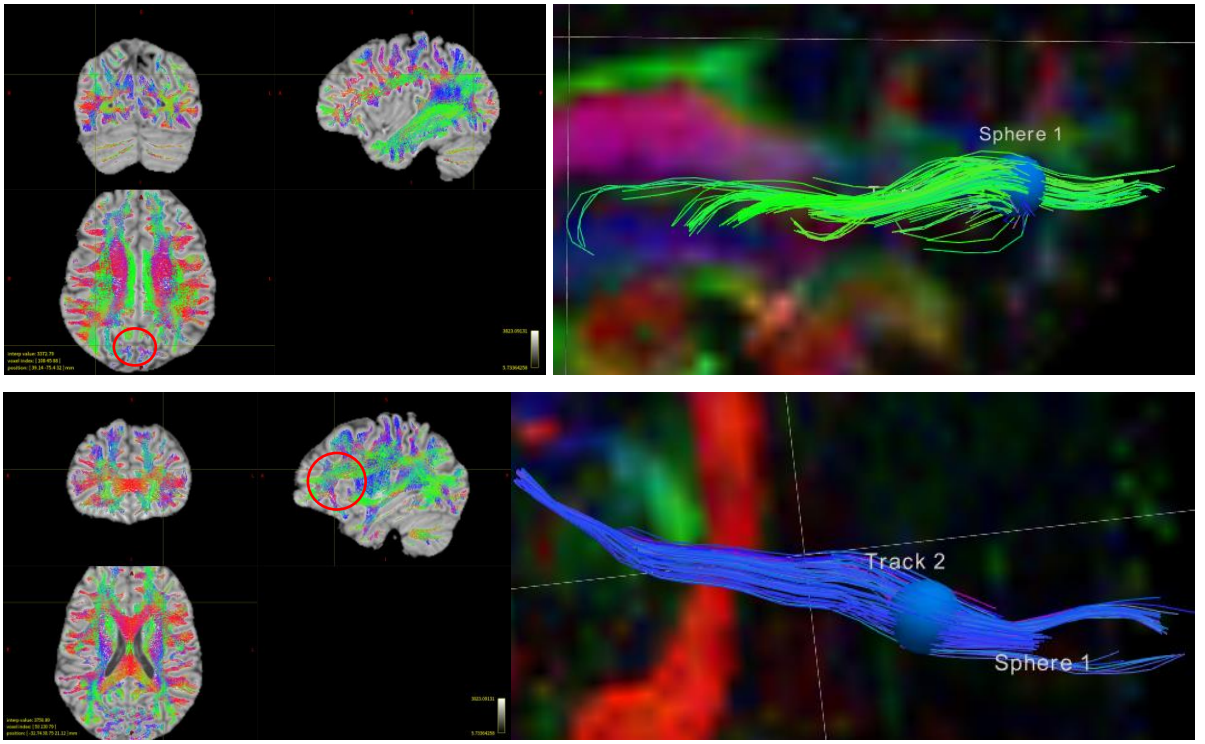

Figure 3. Method 1: Comparisons of fiber bundles in Trackvis and MRtrix.

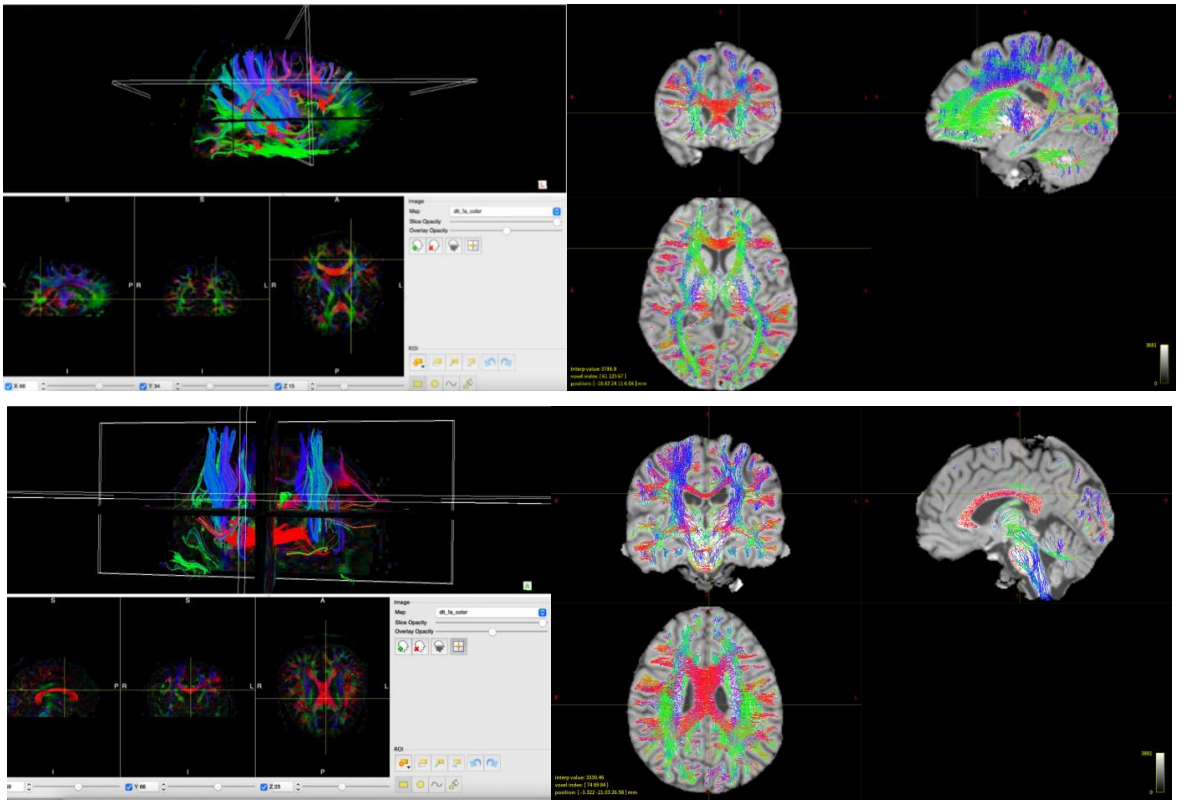

Figure 4. Method 2: Comparison of fiber bundles in Trackvis and MRtrix.

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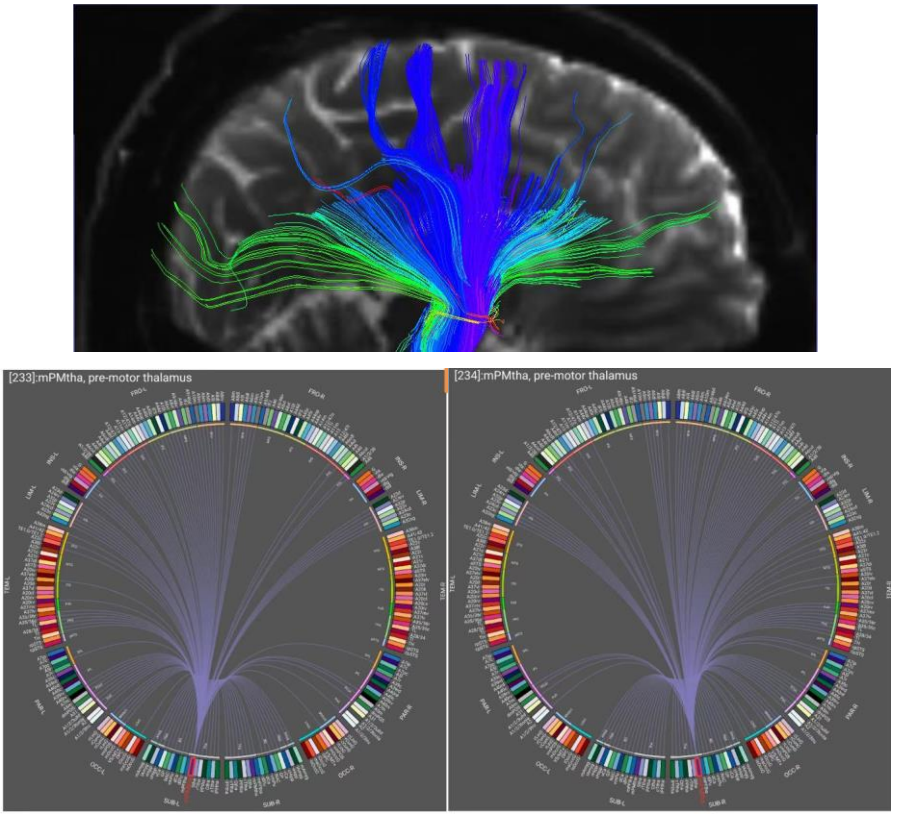

Figure 5. Method 3: Comparison of fiber bundles in 3D Slicer and Brainnetome Atlas website.

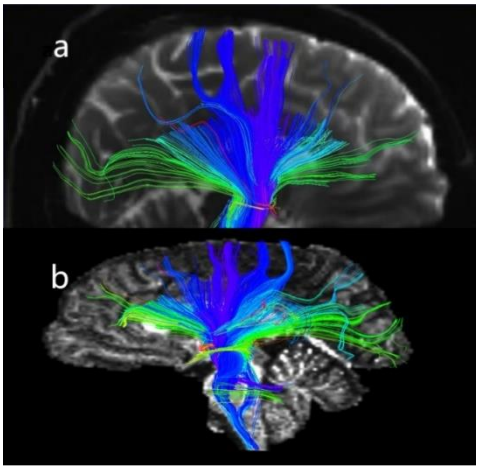

Figure 6. Fiber bundles made using 3D Slicer in this experiment(a) and The fiber bundle made by that doctor using 3D Slicer.

Then, because it goes through the thalamus, the fiber bundles obtained by the third method were compared with these two fiber bundles on the Brainnetome Atlas website [6], which represent the junction of the left and right halves of the thalamus. And when we compared the region of the brain where the nerve bundle ends with the map here, they went roughly the same way (As shown in Figure 5). Then, on the 3D Slicer forum, a doctor's presentation on the fiber bundles of the normal human brain region thalamus was found and compared (As shown in Figure 6).

It can be concluded that the whole brain fiber bundle imaging of the subjects has been successfully reconstructed, and it is not significantly different from normal human brain fiber bundles.

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3.2. *Variation of the number of fiber bundles at different angle threshold*

Here are screenshots of the data starting from 5 degrees, every 5 degrees, and continuing until 90 degrees (As shown in Figure 7). Their horizontal axis represents the length of the fiber bundle, and their vertical axis represents the number of fiber bundles. It can be seen that there is a certain quantitative relationship between them (As shown in Figure 8).

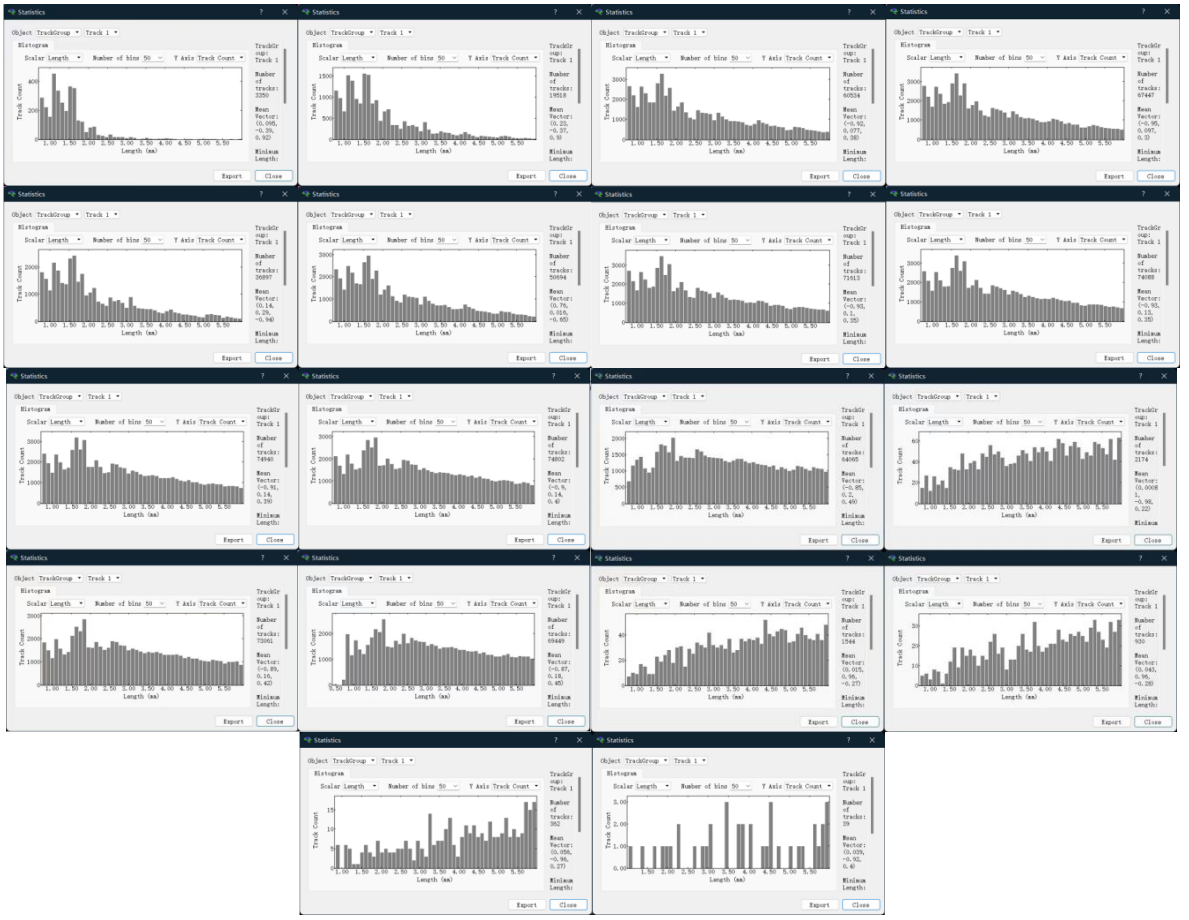

Figure 7. Starting from 5 degrees and every 5 degrees, take screenshots of the data up to 90 degrees.

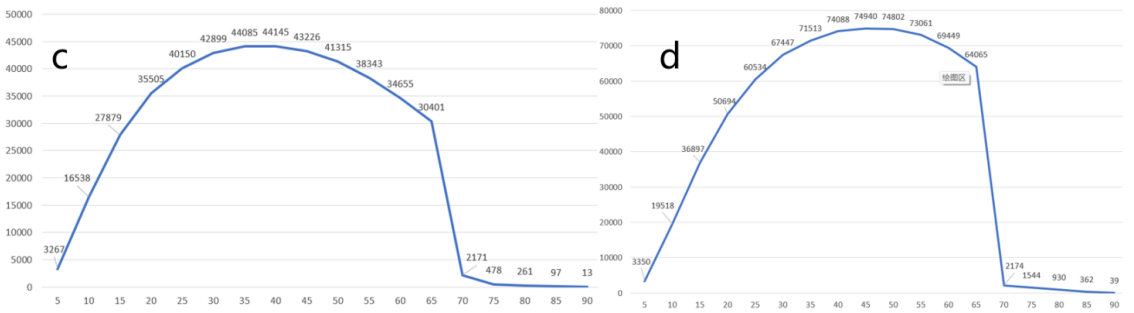

Figure 8. Linear relationship between angle threshold and number of fiber bundles when the fiber bundle length is 3mm(c) and 6mm(d).

3.3. *Strength of the connections between the left and right brain*

The following are the p-values between several brain regions. It can be seen that as the p-value decreases, the difference in structural connectivity strength between these two brain regions in the left and right brains becomes more significant.

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Table 1. p-values between several brain regions

Brain regions	**p-value**
Primary Visual Cortex-Medial Superior Temporal Area	0.0007460001847930087
Primary Visual Cortex-Parieto-Occipital Sulcus Area 2	0.0007161131199702864
Primary Visual Cortex-Area p32	0.00013377678931128091
Primary Motor Cortex- Area STGa	0.00023992966090779843
Third Visual Area-Area posterior 9-46v	0.0008655371960971986
Premotor Eye Field-Primary Sensory Cortex	0.0004037378892184886
Area 55b-Area p32	0.00014378310396516235
IntraParietal Sulcus Area 1-Fusiform Face Complex	0.008159259939707501
Area Lateral Occipital 1-Medial IntraParietal Area	0.00010544610447256061
Middle Temporal Area-Lateral Area 7A	0.002190673004273396

4. Conclusion

In this experiment, we successfully reconstructed the whole brain fiber bundle image, explored the relationship between the Angle and the number of fiber bundles, and compared the strength of structural connections between the left and right brain. We hope that this linear map of the relationship between the Angle and the number of fiber bundles will be useful to anyone who wants to explore aspects of mental illness in the future. The limitation of our experiment is that the raw data had some problems, which caused us not to be able to register the atlas template. And in DTI, the signal-to-noise ratio is also a headache issue. Moreover, in deterministic fiber bundle tracking, it is difficult to manipulate some intersecting fiber bundles, which is also a problem. Fortunately, Trackvis software has helped solve this problem.

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