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A preliminary exploration of brain fiber bundle reconstruction and its influencing factors based on diffusion tensor imaging

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Abstract. This paper focuses on the methods and progress of brain fiber bundle construction based on diffusion tensor imaging data, and conducts a preliminary exploration of the construction results. The study is based on 45 subjects in the public database, using different software to construct nerve fiber bundles for comparison, calculating the number of fiber bundle tracking under different parameters, and finally conducting a t-test on the fiber bundle connection strength of the left and right brain. The nerve fibers constructed by different software are relatively consistent and also consistent with human brain nerve fibers. A more relaxed length threshold will increase the number of fiber tracking, and as the angle threshold increases, the number of fiber tracking will first increase and then decrease. There are differences in the connection strength of the left and right brain. This preliminary study provides a foundation for further exploring brain connectivity and analyzing differences between individuals or patient groups. While the fiber bundles constructed matched expectations, more validation is needed against post-mortem dissections or other imaging techniques. Additionally, expanding the study to include more subjects and analyzing specific fiber bundles or regions could provide more detailed insights. The methods and parameters evaluated in this work help establish best practices for fiber tracking and analyzing connectivity strength metrics. With refinement, such fiber bundle analysis tools may help researchers better understand structural brain networks and differences related to development, aging or disease.

Keywords: DTI, tractography, fiber bundles, structural strength

1. Introduction

1.1. DWI

Diffusion Weighted Imaging (DWI) is a widely used medical imaging technique in the field of radiology [1], mainly used for Magnetic Resonance Imaging (MRI) scans. Its imaging principle is based on the phenomenon of Brownian motion, that is, the random motion of water molecules. In biological tissues, the continuous motion of water molecules is due to the presence of thermal energy. However, it should be noted that the movement of water molecules is affected by factors such as cell structure, cell membrane, and other cell components, which limit the movement of water molecules.

DWI uses special gradients to measure the speed at which water molecules diffuse in different directions within cell tissues, thus taking advantage of this phenomenon. A relatively high magnetic resonance imaging signal indicates that water diffusion in a specific area is not restricted. Conversely, when the diffusion of water is hindered or restricted, the magnetic resonance imaging signal will decrease. In fact, a DWI scan consists of many images obtained using different gradient intensities (called b values). The higher the b value, the greater the diffusion weighting of the image. Clinicians can generate maps showing the apparent diffusion coefficient (ADC) of water in different tissues by analyzing the signal intensity of these images. ADC maps can display the direction and speed of water diffusion, which is of great significance for understanding the microstructure of tissues.

1.2. DTI

Diffusion Tensor Imaging (DTI) is an advancement of the DWI method, obtaining detailed information about the diffusion of water molecules in tissues. DTI is obtained by capturing a large number of DWI images and using diffusion gradients in different non-collinear directions. The captured images can be used to calculate the diffusion tensor, which is a mathematical model used to describe the three-dimensional diffusion behavior of water in each voxel (three-dimensional pixel) in the tissue. The diffusion tensor in DTI represents the extent and process of water diffusion along three principal axes.

Fundamentally, DTI uses a more complex and informative method derived from DWI, playing a key role in observing the microstructure of tissues and the organization of white matter tracts in the brain. Therefore, it is an unparalleled asset in the field of neuroscience. Its main purpose is to observe fiber tracts, help formulate preoperative surgical plans, and evaluate brain function after surgery.

1.3. Tractography

Tractography is a technique in Diffusion Tensor Imaging (DTI) used for analyzing neural pathways or fiber tracts in the brain [2]. This method is based on the principle that water within white matter fibers flows along the direction of the fibers, not perpendicular to them, thus forming an image of the fiber bundles in the brain. The method is straightforward and excludes subjective evaluations to maintain objectivity.

Fiber bundles are color-coded according to their direction. For example, fibers from left to right are red, fibers from front to back are green, and fibers from top to bottom are blue. They can be analyzed through three-dimensional visualization.

There are mainly two types of fiber tractography: deterministic fiber tractography and probabilistic fiber tractography [3]. Deterministic fiber tractography: This method is based on the assumption that the main diffusion direction of any given voxel (the smallest visible box-shaped part in a three-dimensional image) represents the direction of the fiber bundle. Moving along this direction from one voxel to another generates the fiber bundle. Although this method is simple and clear with high computational efficiency, it performs poorly in areas where fiber bundles cross, bend sharply, or diverge.

It is suggested to use another method–probabilistic fiber tractography because it takes into account the inherent uncertainty of directionality. The probabilistic technique based on voxels does not assume a single direction but creates a distribution of possible directions and generates various potential paths. This method can better handle areas where fibers cross or branch, thus more comprehensively describing complex brain connections. However, this method requires a large amount of computation, so it takes longer.

Fiber bundle imaging is extremely beneficial for neurosurgical operation planning because it allows surgeons to avoid damaging key fiber bundles. It can also be used to study diseases affecting brain white matter, such as multiple sclerosis, and explore interconnections in the brain.

Despite being based on the same principle, choosing different fiber reconstruction methods and parameters will affect reconstruction results; different research purposes or attention to fiber connections between different brain regions also require selection of different parameters. Therefore, we will use different methods to construct whole-brain fiber bundles in this study and compare fiber bundles constructed by different methods. At the same time we will also select different parameters for repeated construction of nerve fiber bundles for comparison; this will allow us to compare how different

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parameters affect fiber tracking results. Finally, we plan to compare fiber bundles from different cerebral hemispheres to explore differences in fiber connections between them.

1.4. Structural Connections Strength

The strength of brain structural connections refers to the strength of neuronal connections between different brain regions, which reflects to some extent the effectiveness of information transmission. Neurons connect through synapses and transmit electronic and chemical signals between different regions. Changes in different connection strengths may be related to cognitive functions, learning, memory and other brain functions. Information about brain structural connection strength usually relates to the degree of neuronal connections between different brain regions and the strength of transmitted information. This connectivity can be studied in various ways, one of which is Diffusion Tensor Imaging (DTI). DTI is a neuroimaging technique used to observe the direction and structure of white matter fiber bundles [4]. Since DTI measures the direction of water molecule diffusion in nerve fiber bundles, it can reveal the direction and connectivity of white matter fibers. By analyzing DTI data, connection information between brain regions can be obtained that relates to brain structural connection strength. DTI can quantitatively measure connectivity in white matter fiber bundles thereby inferring structural connection strength between brain regions. By combining DTI data with other neuroimaging data we can gain a more comprehensive understanding of brain network structure and function as well as interactions between different regions.

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2. Methods

The data in this study comes from the HCP database. We randomly selected the diffusion tensor imaging data of 45 subjects and conducted fiber bundle construction and statistical analysis on it.

2.1. Construction of nerve fiber bundles

We chose Trackvis and MRtrix software to perform deterministic fiber tracking reconstruction of nerve fiber bundles on the same diffusion tensor imaging data. The construction process follows the following steps: (1) Select the coordinates of the x, y, z axes to construct the ROI sphere. In this step, we will get all the fiber bundles that pass through this area, including all directions and different lengths of fiber bundles; (2) Set the fiber length threshold, based on the threshold to screen all constructed fiber bundles, too long (greater than the threshold) or too short (less than the threshold) fiber bundles will be eliminated. This step will remove the messy fiber bundles around the ROI; (3) Use 3D Slicer software for fiber bundle rendering. This software can reduce the rendering range of fiber bundles to obtain a suitable range of fiber bundles. Afterwards, we compared the fiber bundles generated in the two software to observe whether the whole brain fiber bundles generated by different software-maintained consistency. Finally, to ensure the accuracy of our obtained fiber bundles, we compared the generated fiber bundles with previous other research tracking results. 2.2. The impact of different fiber bundle tracking parameters on construction results

In this part of the study, we chose different angle thresholds for fiber bundle tracking. The angle range is 0~90°, and tracking is performed every time it increases by 5°, and the number of fibers obtained at each angle is recorded. In addition, we also set different fiber length thresholds, two types: 0-3mm and 0-6mm, and statistics were made on the number of fibers obtained under different length thresholds.

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Finally, we presented the number of fibers obtained under different length thresholds and angle thresholds.

2.2. Analysis of connection strength differences between left and right brain

In this part of the study, we included all 45 subjects. We divided the left and right brains separately, calculated the fiber connection strength between different brain regions in both hemispheres, standardized all subjects' connection strength, and performed independent sample t-tests on the same brain region connection strength between left and right cerebral hemispheres to compare whether there are significant differences in connection strength between same brain regions in left and right brain. The significance level was chosen as $P<0.05$ and $P<0.005$.

3. Results

3.1. Construction of nerve fiber bundles

Through fiber bundle tracking, we constructed whole brain fiber bundles, as shown in Figure 1, which is the construction result of Trackvis software.

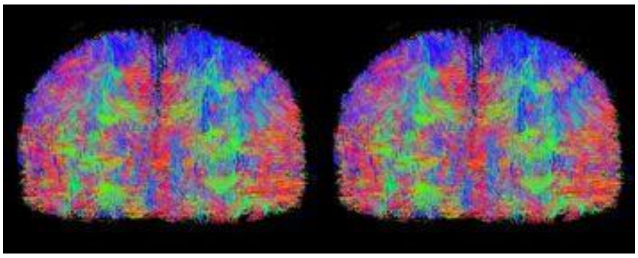

Figure 1. Whole brain nerve fiber bundles constructed using Trackvis

We used 3D Slicer to compare the whole brain nerve fibers constructed by Trackvis and MRtrix respectively. As shown in Figure 2, it can be found that the fiber bundles constructed by the two software are relatively consistent.

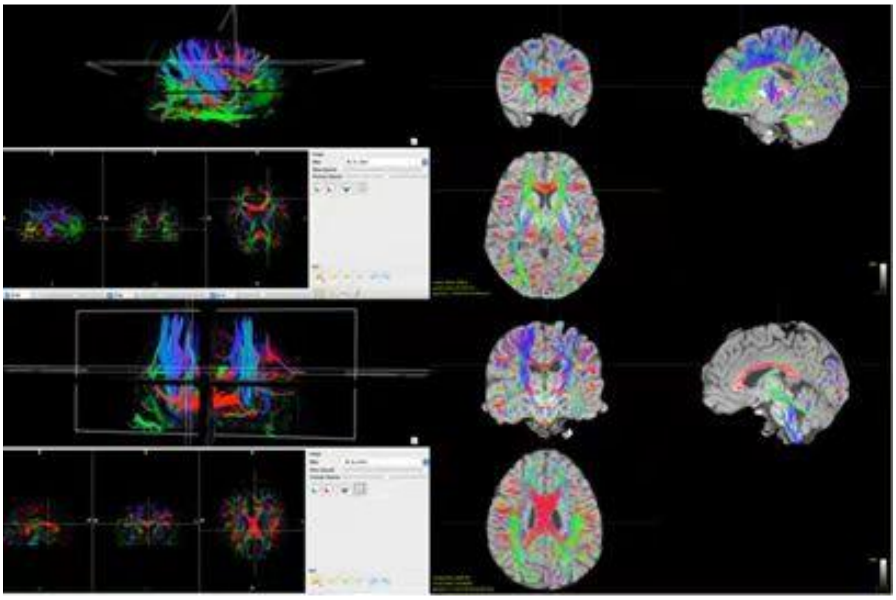

Figure 2. Nerve fiber bundles constructed using Trackvis and MRtrix respectively

Next, we selected the fiber bundles that passed through specific brain regions and presented the results of the two software respectively, as shown in Figure 3.

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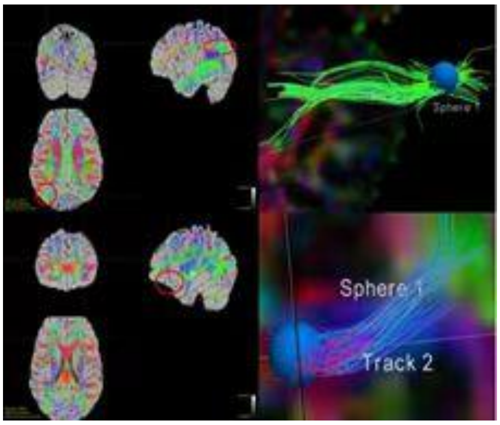

Figure 3. Comparison of fiber bundles passing through specific brain regions in Trackvis and MRtrix

Of these, the fibre bundles passing through the thalamus are shown in Figure 4.

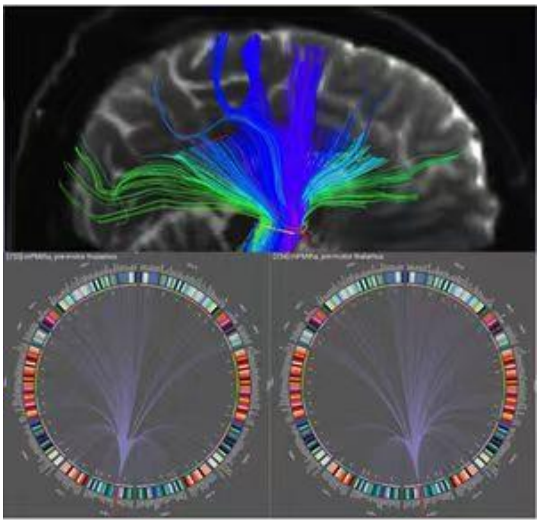

Figure 4. Fiber bundles passing through the thalamus

Finally, we compared the fiber bundles passing through the thalamus constructed in this study with the normal human brain thalamus fiber bundles (sourced from the 3D Slicer forum), see Figure 5. It can be seen that the results constructed in this study are consistent with the normal human brain thalamus fiber bundles.

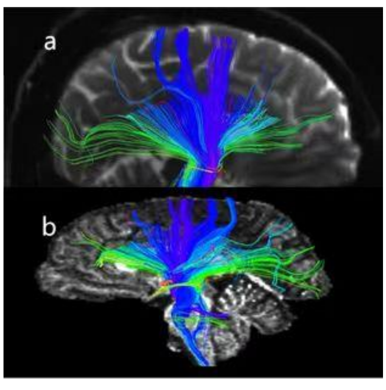

Figure 5. Thalamic fiber bundles constructed in this study(a), Normal human brain thalamic fiber bundle(b)

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3.2. The impact of different fiber bundle tracking parameters on construction results

Using different angles and length thresholds, we obtained different numbers of fibers, as shown in Figure 6, where the y-axis is the number of whole brain fiber bundles constructed, and the x-axis is different angle threshold parameters. The left side is the number of fibers with a length threshold of 0-3mm, and the right side is the number of fibers with a length threshold of 0-6mm.

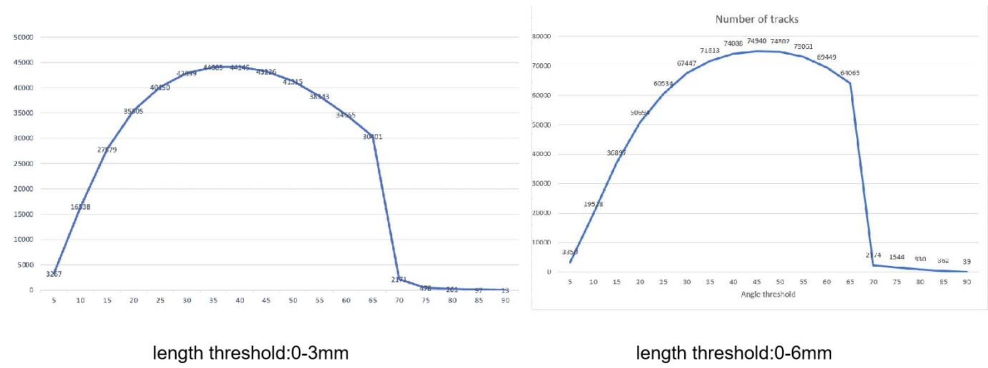

Figure 6. Number of fiber bundles under different angle thresholds and length thresholds

It can be seen that when the fiber length threshold is wider, more fiber bundles will be obtained under the same angle threshold; at the same time, as the angle threshold increases, the number of fiber bundles shows a trend of first increasing and then decreasing, and there is a significant decrease in the number of fiber bundles at 65°-70°. At the same time, we also noticed that the angles at which different fiber length thresholds have different numbers of fibers are not consistent. As shown in Figure 7, when the length threshold is 0-3mm, the number of fibers reaches a maximum of 44145 at an angle threshold of 40°, while when the length threshold is 0-6mm, The number of fibers reached a maximum of 74940 at an angle threshold of 45°.

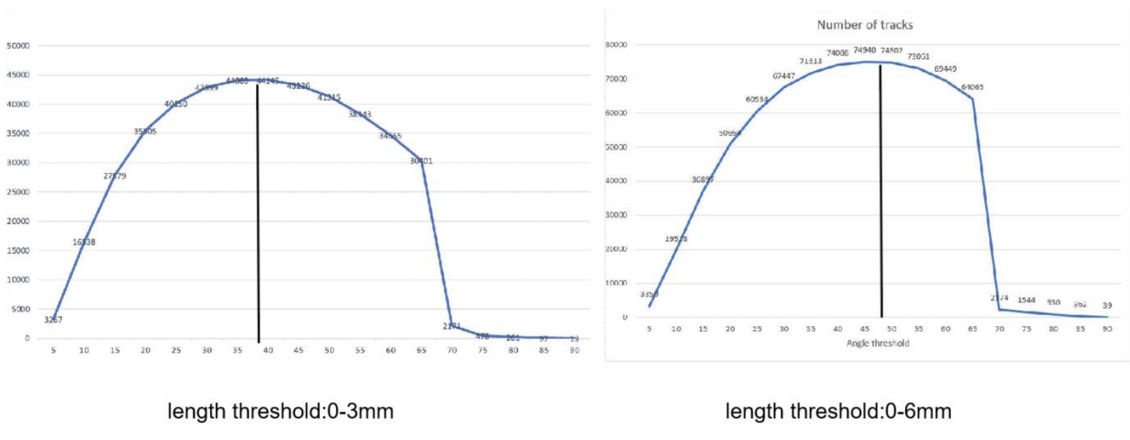

Figure 7. Angle thresholds corresponding to maximum number of fiber bundles under different length thresholds

3.3. Analysis of connection strength differences between left and right brain

We compared the fiber connection strength of primary visual cortex in left and right brains. The comparison results are as follows Table 1. It can be seen that in these brain regions P value is less than 0.05, that is, in left and right brains, there are differences in fiber connection strength between primary visual cortex regions. Among all fibers (32400), there are 14006 (43.22%) results with P<0.05 and 9021 (27.84%) results with P<0.005. For specific results see supplementary materials (0.05.txt and 0.005.txt).

Table 1. P value of Primary Visual Cortex

	Primary Visual Cortex
Sixth Visual Area	0.0007460001847930087
Area 55b	3.465135579979602e-07
Area V3A	0.006967175655108352
Area Lateral Occipital 1	0.013550145156041296
Superior Frontal Language Area	0.0066502136609650365

4. Discussion

In this study, we successfully constructed similar brain fiber bundles based on different software, which indicates that existing software and techniques can achieve relatively consistent whole brain fiber tracking [5]. At the same time, the fiber bundles we constructed also maintained a high consistency with the results of normal human nerve fibers, which indicates that the constructed fiber bundles have a high practical significance, and using fiber tracking for fiber bundle reconstruction helps to promote our understanding and exploration of human brain fiber bundle connections.

Further analysis of different parameters also made us realize the impact of length threshold and angle threshold on fiber tracking results [6]. Increasing the length threshold range can significantly increase the number of fibers obtained by tracking, but the rapid decrease in the number of fibers that occurred between 65°-70°, and in the construction of fibers with different length thresholds, also conforms to this characteristic. This result is puzzling. It seems to be related to the actual situation of neurons in the brain. There are fewer large turning angles in the nerve fibers in the human brain, and therefore different length thresholds have a smaller impact on such results. Finally, when the length threshold increases, the angle threshold at which the maximum number of fibers is obtained also increases. The possibility of higher turning angles in longer fiber bundles is also higher. This also suggests that when the target fiber bundle length is different, attention to the angle threshold should also be correspondingly increased.

Finally, there are differences in connection strength between left and right brains [7]. Although cerebral hemispheres are morphologically similar, previous studies have pointed out that left and right hemispheres each undertake different cognitive psychological functions. The differences in this study may also reflect similar facts. More in-depth exploration of brain regions with differences may help improve our understanding and understanding of functional differences between left and right brains.

The lack of mastery of methodology makes us feel difficult in result presentation and further analysis, which is also part of our strengthening in future research.

5. Conclusion

Existing software can construct relatively consistent fiber bundles quickly and conveniently, and these fiber bundles can reflect nerve fibers in the brain. Different length thresholds and angle thresholds will affect the results of fiber bundle tracking, and different research may need to consider using different parameters. Different parameters indeed have a noticeable impact on tracking results, which suggests that even when conducting the same research, important differences may arise due to variations in imaging techniques. Comparisons of results from different studies may be significantly affected. Overcoming the impact brought about by different parameters is a challenge. Possible solutions include using uniform parameters or integrating different parameters for multiple calculations and analyses. This indeed requires further exploration and will be the direction of our future research.

There are differences in fiber connection strength between left and right hemispheres. The exploration of differences between the left and right brain can become our fixed direction. Whether the results produced under different parameters are related to different levels of brain function, such as clearly located sensory signals and widely distributed and uncertain high-level cognitive functions.

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Perhaps different parameters will correspond to these different brain functions, which is also what we are interested in.

This study provided a preliminary exploration of brain fiber bundle construction methods and their results. While the fiber bundles constructed appeared consistent with human neuroanatomy and were replicated across software, more validation is still needed against other data or imaging techniques to fully verify the accuracy of the fiber tracking approaches. Additionally, expanding the sample size and focusing analyses on specific fiber bundles or brain regions could help gain more detailed and robust insights. Nevertheless, this work helped establish some best practices for fiber tracking and connectivity analysis that can be built upon in future studies. With continued refinement of the methodology and larger-scale applications, quantitative fiber bundle analysis has the potential to advance our understanding of structural brain networks and organization, as well as differences related to factors like development, aging and disease.

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