

Tractography of the subcortical U-fibers using a position-dependent maximum angle

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Synopsis

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Short association fibers in the subcortical white matter, also known as U-fibers, represent the connections between neighboring gyri. Due to the geometry of the cortical folds and the sharp turns along the cortical surface, tractography of U-fibers remains a challenge since increasing the maximum angle between tractography steps also increases the occurrence of false positive streamlines. We propose to replace the fixed maximum angle value in tractography algorithms by an *angular map*, allowing higher angles at the interface between grey and white matter. This enables a more accurate tracking of U-fibers, while keeping a low number of false positive streamlines.

Introduction

Subcortical U-fibers are short association fibers within the cortex or in the outer parts of the subcortical white matter representing connections between neighboring cortical areas. U-fibers are thought to be involved in multiple neurological and psychiatric diseases, such as in multiple sclerosis¹ and Alzheimer's disease². Tracking U-fibers is more challenging compared to main white matter tracts due to the geometry of the cortical folds, requiring sharp turns to cover the cortical surface³. Obtaining U-fibers in a whole-brain tractogram requires a higher maximum angle between tractography steps to follow subcortical fibers along the cortical folds. However, a higher maximum angle increases the probability of generating false positive streamlines, increasing the post-processing steps required to clean the obtained tracts.

We propose to replace the fixed maximum angle value in tractography algorithms by an angular map, which allows different values of maximum angle between tractography steps depending on the position in the brain. Allowing a higher angle at the interface between grey and white matter, with lower values in deep white matter, enables a more accurate tracking of subcortical U-fibers in whole-brain tractograms, while keeping a low number of false positive streamlines.

Methods

Modified tractography algorithm

We adapted the probabilistic tractography algorithm from DIPY⁴ to allow arrays in addition to single scalar values as input parameter for the maximum angle variable α_{max} . The maximum angle variable becomes an *angular map* (Fig. 1A) dependent on the position (x, y, z) of the tractography step

$$\alpha_{max} \rightarrow \alpha_{max}(x, y, z), \quad (1)$$

which impacts the adjacency matrix $M_{adj} \in \{0, 1\}^{d \times d}$ used to compute the allowed directions from

the current direction $\hat{d}$. The probability mass function pmf bounded by α_{max} is obtained by

$$pmf_{lim} = pmf(x, y, z) * M_{adj}(\alpha_{max}(x, y, z), \hat{d}). \quad (2)$$

The new direction is then selected amongst the directions which have a $pmf_{lim} > 0$ in a classic probabilistic tractography approach.

Data

Firstly, an in-vivo dMRI scan of a healthy adult participant was performed on a 3T GE SIGNA Premier scanner with the following parameters: TR = 4842 ms, TE = 77 ms, 2 mm isotropic voxels, 64 gradients at $b = 1000$, 32 at $b = 2000, 3000, 5000$ s/mm², and 7 interspersed b_0 images. Preprocessing included thermal denoising⁵, Gibbs ringing correction⁶, eddy-current distortion and movement correction⁷. A 3D T1 image (TE = 2.96ms, TR = 2188.16ms, TI = 900ms, 156 slices, 1mm isotropic, in-plane FOV: 256x256mm²) was also acquired. Three regions of interests (ROIs) were placed in the hand motor cortex, somatosensory cortex and in the middle frontal gyrus to isolate U-fibers between adjacent gyri. The right middle frontal gyrus is responsible for numeracy⁸, which is linked to hand motor function⁹. Registration to the Desikan-Killiany atlas¹⁰ was accomplished using *FreeSurfer*. The frontoparietal part of the arcuate fasciculus (AF) tract was extracted from the whole brain tractography using White Matter Query Language¹¹.

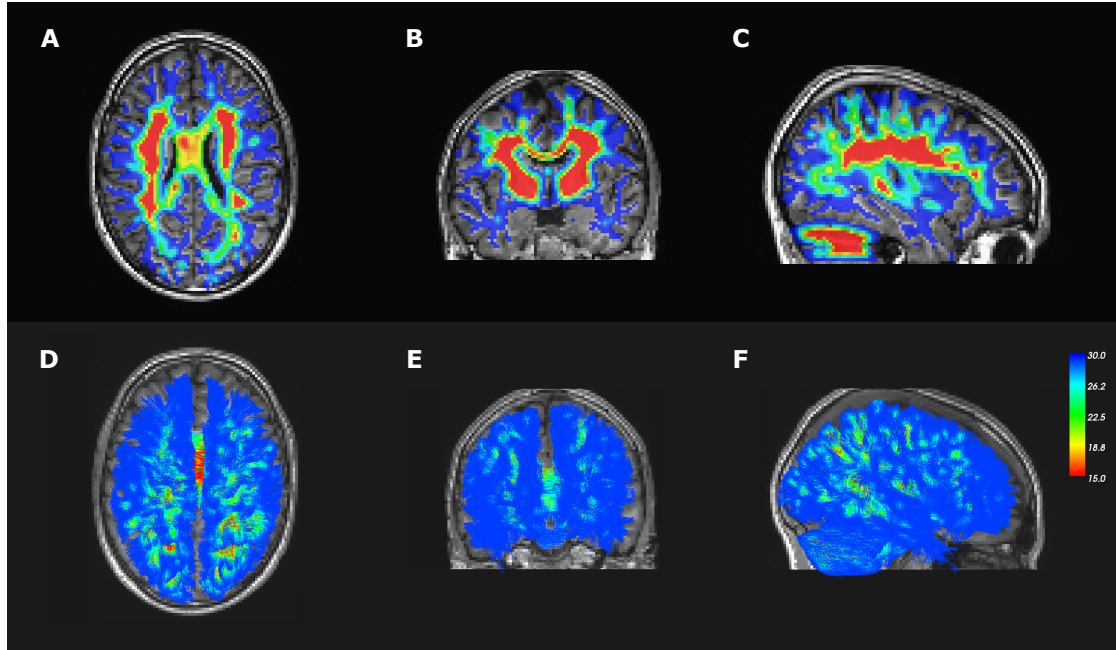


Figure 1: 2D slice of the angular map in **A** axial, **B** coronal and **C** sagittal view. Tractogram obtained using the varying maximum angle values in the angular map, in **D** axial, **E** coronal and **F** sagittal view. Low and high maximum angle values are represented in red and blue, respectively.

Secondly, a synthetic phantom from the Diffusion-Simulated Connectivity (DiSCo) dataset¹² (Fig. 2A) was used to compare the connectivity measures of 16 regions to a known ground truth. The dMRI protocol was composed of 360 gradients, equally spread over 4 b-value shells ($b=1000, 1925, 3094$,

13191 s/mm²). The DiSCo1 phantom was selected in the 2x2x2mm resolution.

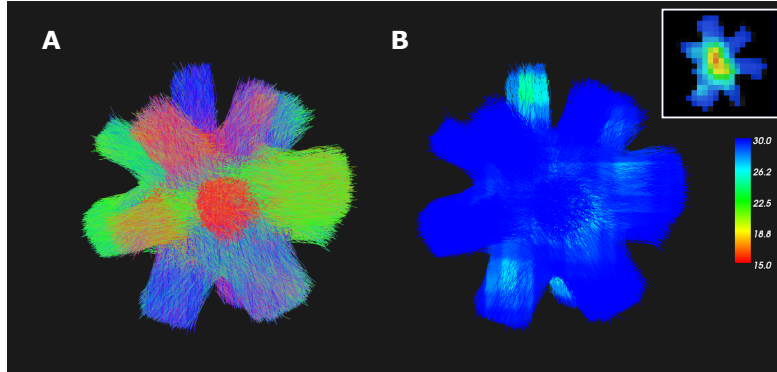


Figure 2: Tractogram of the DiSCo1 dataset using the varying angle with **A** directional colors and **B** the varying angle values of the angular map. Low and high maximum angle values are represented in red and blue, respectively.

The local modeling of the in-vivo and synthetic data was performed with multi-shell multi-tissue spherical deconvolution (msmt-CSD)¹³. The modified probabilistic tractography described in the previous section was tested with an angular map based on the white matter fiber orientation distribution (FOD) obtained with msmt-CSD with $15^\circ < \alpha_{max} < 30^\circ$ (Fig. 1: in-vivo; Fig. 2: synthetic data). The results were compared to the default probabilistic algorithm with $\alpha_{max} = 15^\circ$ and $\alpha_{max} = 30^\circ$.

The tractograms obtained from the synthetic data were filtered with SIFT¹⁴ and the connectivity matrices between the 16 ROIs were computed.

Results & Discussion

U-fibers

The streamlines linking the motor cortex to the adjacent gyri isolated from the tractogram in Fig. 1F are displayed in Fig. 3. The maximum angle of 15° (Fig. 3A) is too low to tract the subcortical connections between the hand motor cortex and somatosensory cortex due to geometry of the cortical fold. A maximum angle of 30° (Fig. 3C) finds a large number of connections between both regions but also produces several false positive streamlines going to deep white matter regions. The varying angle ranging from 15° to 30° produces no such streamlines while connecting both gyri to the motor cortex, without the need of exclusion zones or further post-processing.

White matter tracts

In the main white matter tracts, such as the frontoparietal part of the AF (Fig. 4), an increase in maximum angle produces more stray and false positive streamlines. As shown in the bottom row of Fig. 4, the angular map allowed for a greater angle near the cortex.

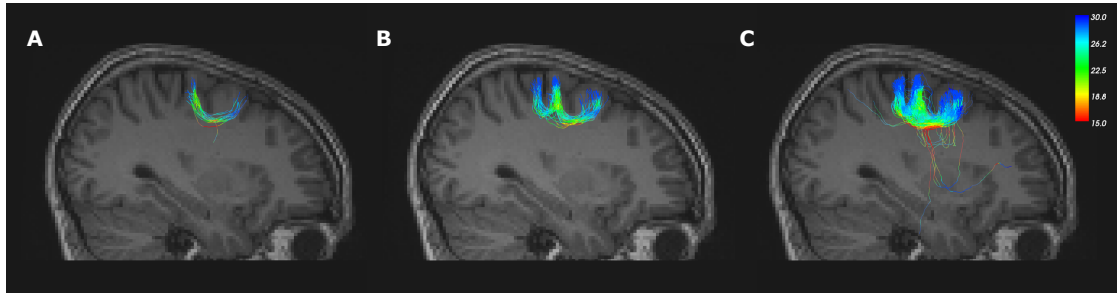


Figure 3: Streamlines connecting the hand motor cortex to the somatosensory cortex and the frontal middle gyrus obtained with **A** a maximum angle of 15°, **B** the varying angle ranging from 15° to 30° based on the angular map and **C** a maximum angle of 30°. All streamlines are colored using the angular map used for B to show how the streamline would have been affected by the varying angle.

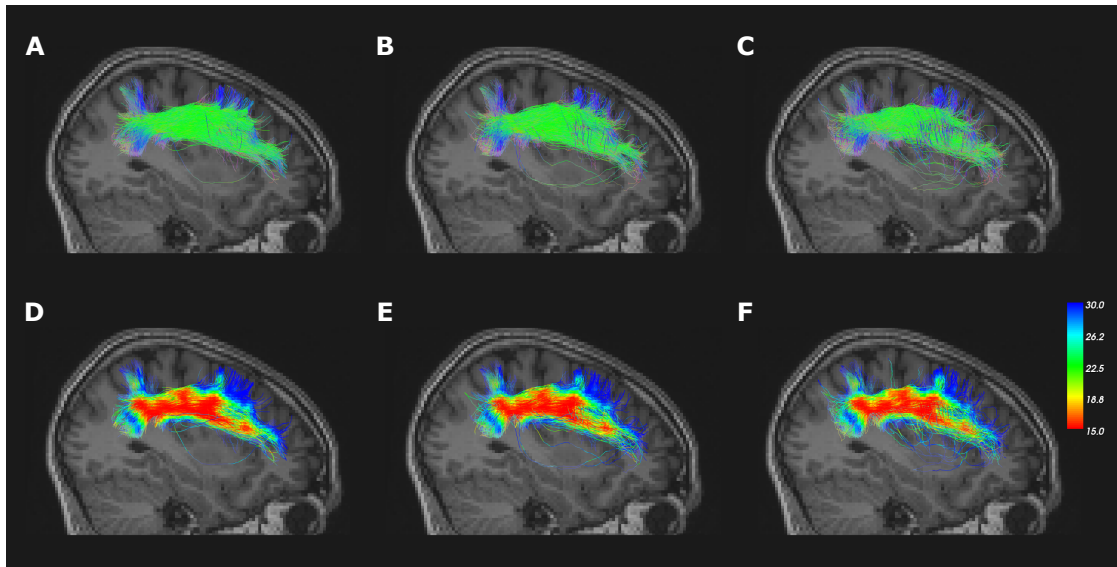


Figure 4: Tract of the frontoparietal part of the arcuate fasciculus obtained with **A,D** a maximum angle of 15°, **B,E** the varying angle ranging from 15° to 30° based on the angular map and **C,F** a maximum angle of 30°. All streamlines in **D,E,F** are colored using the angular map used for **B** to show how the streamline would have been affected by the varying angle.

DiSCo Phantom

The connectivity matrices obtained in the DiSCo1 dataset in Fig. 5 show the lowest correlation to the ground truth with a maximum angle of 15°. This angle also produced two false negatives between ROI 7 and ROI 2 & 4, which are both adjacent to ROI 7 and require a high angle to connect. This configuration is similar to the geometry presented by U-fibers. Using the angular map or the 30° angle produced similar scores, except for a higher number of false positive streamlines in the 30° angle.

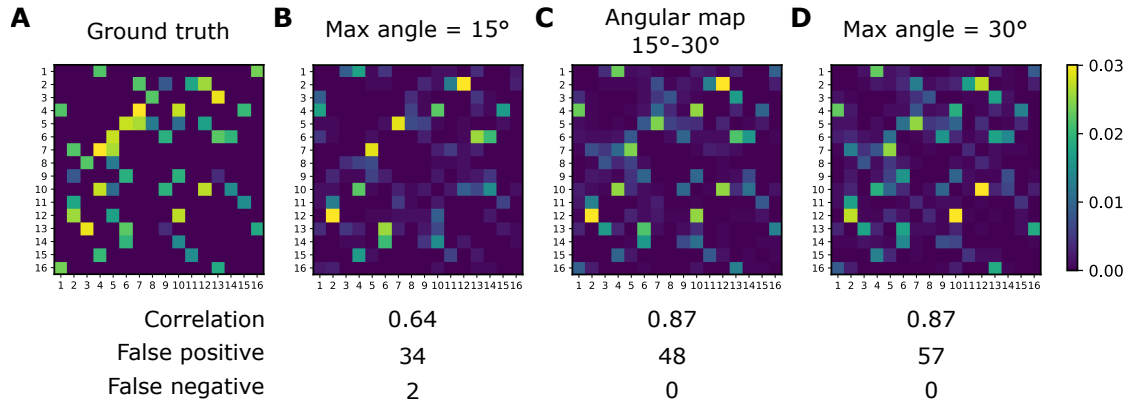


Figure 5: Connectivity matrices of the DiSCo1 dataset with **A** the ground truth values, **B** a maximum angle of 15°, **C** the varying angle ranging from 15° to 30° based on the angular map and **D** a maximum angle of 30°. All matrices are symmetric, and are normalized to sum to one.

Conclusion

The results can be improved by refining the angular map created, such as using anatomical T1 information to better delimitate the subcortical white matter. Nonetheless, the inclusion of an adaptive maximum angle allows for a more accurate tracking of subcortical U-fibers along the cortical folds, without generating as many false positive streamlines as a global increase of the maximum angle. Incorporating this change into tractography algorithms might improve the accuracy of the tractograms produced, especially for subcortical fibers.

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