Generalized DTI Fiber Tracking in Continuous Tensor Field

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Introduction

One of the most important advantages of diffusion tensor imaging (DTI) is its ability to delineate fiber tracks in a noninvasive manner since the eigenvectors of diffusion tensors can be used to reveal functional connectivity through fiber tracking or tractography. In order to obtain reliable tracking results under the most widely used settings in current clinical trials of DTI experiments, we propose a generalized streamline tracking technique on a continuous vector field framework with a unified tracking termination criterion. Our strategy is to use a highly accurate tracking algorithm based on the fourth order Runger-Kutta method and a unified termination criterion to achieve reliable and robust tracking results on a tissue property integrated continuous vector field.

Generalized Streamline Fiber Tracking

Theoretically, a voxel, which is commonly treated as a homogeneous block, can be considered as a point; and the image data can be generalized into a continuous framework by connecting the discrete data points into a continuous volume in 3D, as human brain white matter fibers are physically continuous and have unique spatial shapes. The naturally accepted concept of voxel can be seen as the nearest neighbor interpolation in a generalized continuous field framework. When the direction and magnitude of a principal eigenvector are treated as flow direction and speed of the velocity vector at that point, the streamline tracking of a white matter fiber is nearly equivalent to streamline tracking in fluid dynamics by solving an initial value ordinary differential equation. For better tracking results, the "velocity" field constructed from the normalized principal eigenvectors can be regulated with anatomical or physiological information. In our implementation, the vector field is simply weighted by FA values to make the algorithm more sensitive to gray matter.

When tracking propagation rules are given, most fiber tracking algorithms to date use the following three criteria to terminate a track: 1) when the track reaches the maximum number of propagation steps; 2) when the track reaches the segmented boundaries or image boundaries; 3) when the track turns any degree larger than a predefined threshold.[1,2] Because these criteria are applied to suppress "unwanted" fibers, user biases are often introduced into the final tracking results. We present a single termination criterion to simplify this problem. This criterion is based on the fact that the diffusion tensor principal eigenvectors are more collimated inside the white matter fibers and more randomly oriented at gray matter and CSF regions. Thus, a track can be naturally terminated when it moves much slower than it does in white matter. This unified termination criterion can reduce the potential inaccuracy introduced by user-defined and potentially biased termination criteria. Moreover, there is no need to segment out the gray matter regions and to monitor the curvature of the track.

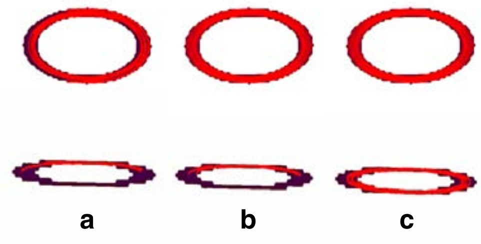

Fig. 1 Tracks overlay on ellipse phantoms. a) Euler's method; b) Runge_Kutta method; c) the generalized streamline fiber tracking. Column a and b tracked under 45 degree turning limit on FA>0.2 segmented regions.

Methods

Due to the present lack of a gold standard for fiber tracking in human DTI, a phantom with a thin band of an ellipse in the center of a 128 x 128 x 128 volume was generated to demonstrate the tracking algorithm. Each voxel inside the band, simulated as white matter, had the same FA value as 0.34, and the fiber orientation was at the tangential direction of the ellipse. The voxels outside the band were simulated as gray matter with FA = 0.1. The intensity of gray matter and white matter was the same. Diffusion weighted images were generated at SNR = 30 by adding Gaussian noise on each image. The diffusion tensors were then calculated from these images using a nonlinear least square fitting algorithm. The simulated fibers were tracked from the same starting points by 1) Euler's algorithm, 2) Runge-Kutta algorithm (both of them were segmented and had the 45 degree maximum turning angle limit), and 3) the generalized streamline fiber tracking with termination criterion as 1/2 step size minimum movement in the field in two consecutive time steps. The continuous field was constructed from tri-linear interpolation on the FA weighed discrete DTI directional field.

To demonstrate the generalized streamline fiber tracking in humans, DTI images were acquired in resolution of 128 x 128 x 58 with 2mm x 2mm x 2.4mm voxel size on GE Excite 3T scanner with one base image and 15 non-collinear diffusion weighted directions.

Results

Fig.1 demonstrates the tracking results on the ellipse phantoms with different tracking algorithms. All algorithms demonstrated adequacy in the ellipse with low eccentricity. For highly eccentric ellipse band, however, the tracing with maximum turning curvature limit was pre-terminated. The sharp turns also caused problem for Euler's method when the streamlines were close to the discrete edges in the voxel view. As expected, our generalized streamline tracking algorithm did not suffer from these limitations and tracked continuously around the ellipse. In humans, our tracking algorithm was able to continuously follow the inferior occipitofrontal fascicle, which has been difficult to track using the conventional methods, as shown in Fig. 2.

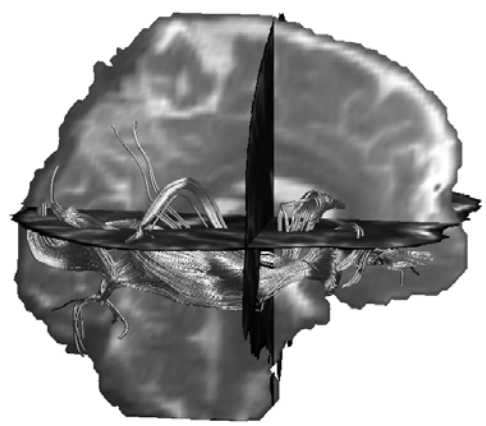

Fig. 2 Inferior occipitofrontal fascicle tracks.

Discussions and conclusions

The method we have developed aims to track fibers using the typical acquisition methods in today's DTI experiments and to obtain reliable tracking results. The reference to neighboring information during continuous field construction, rather than relying on information of one voxel alone, reduces the sensitivity to corrupted local directional information computed from the diffusion tensors. This also helps to reduce erroneous forks and recovers the actual trajectories masked by partial volume effects. The unified termination criterion could reduce the possible biases introduced by user-defined termination criteria. At the same time, this method can incorporate other tracking criteria when the users think they are necessary. It also encourages the incorporation of tissue property integrated tracking. For example, the tensor deflection (TEND) technique can be integrated into the tracking by extending TEND into the continuous tensor field model.[3]

Reference

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3. Lazar M, et al. Hum Brain Mapp 2003;18(4):306-321.