Density Regularized Fiber Tractography of the Brain White Matter using Diffusion Tensor MRI

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Introduction

Diffusion Tensor Imaging (DTI) can disclose the spatial organization of fibrous tissue. More specifically, tractography can be applied to the diffusion tensor field of a human brain resulting in pathways that represent the axonal tracts. However, deterministic streamline propagation techniques are very sensitive to noise due to error accumulation along their pathways, introducing many spurious tracts [1]. Probabilistic tractography methods on the other hand result in connectivity likelihood maps but are not able to visualize rigidly wired tracts [2, 3].

In this work, we propose a novel streamline algorithm that diminishes the influence of noise and estimates the probability for each point along every tract by taking into account the architectural environment. The new algorithm is based on *Density Regularization* (DR) and adds a new stopping criterion to the widely used constraints such as minimal Fractional Anisotropy (FA) and maximum curvature. This new criterion allows tracking fibers more accurately in regions with low FA.

Theory

As described in [4], the trajectories of neighbouring tracts play a dominant role in determining the reproducibility of the tracking result. With DR, we intend to stabilize the tracking solution by incorporating the a priori knowledge that two tracks, initialized from two proximate seed points, i.e. within one axonal bundle, should remain closely together for most of their path length. The latter is not always assured in classic streamline propagation when the signal-to-noise ratio (SNR) is low.

Density Regularized Fiber Tracking (DRFT) is performed by simultaneously propagating a number (N) of temporary tracks (typically N = 27 new seed points are created in the vicinity of every user-defined seed point). After every step, the centre of mass (CM) and the distances d_i (with i = 1, …, N) of the current end points to that CM are calculated. Temporary tracks are only stopped when they tend to veer off-course (i.e. when $d_i > m_d + 1.7\sigma_d$; with m_d and σ_d respectively the mean and the standard deviation of the distances). When one or more of the temporary tracks become spurious, tracking of the CM continues with less temporary tracks, until the CM pathway reaches a region where the FA is too low, the curvature too high, or the density (ρ) of temporary tracks around the CM becomes too low ($\rho \sim 1/m_d < \rho_m$, with ρ_m the user-defined minimal density). Also, the density or the number of temporary tracks around each point of the CM tract can be considered as an estimate of probability along that tract.

Material and methods

A synthetic DT-MRI phantom containing 729 fibers, each with random positions and values (within realistic ranges) for local curvature and FA, was used to validate the DRFT algorithm [5]. We compared different algorithms by calculating the similarity (S) between the synthetic fiber tracts and the experimentally reconstructed tracts, based on the Corresponding Segment Ratio (R_{CS}) and the Mean Euclidian Distance (MED) of corresponding fiber pathways: $S = R_{CS} \exp(-MED)$ [6].

DRFT was also performed on in vivo data of the human brain, which were acquired on a 1.5T Siemens Symphony, using a diffusion weighted twice-refocused spin echo EPI sequence which reduces eddy current induced image distortion. (b-value = 1000 [s mm^{-2}], NEX = 10, 6 diffusion gradient orientations, 128 x 128 x 46 matrix of isotropic voxels (2.2 mm)^3).

Results

When comparing the DRFT versions with the classical versions of Principal Diffusion Direction tracking (PDD) and the Westin tensor deflection method (WEST, [7]) we clearly see that DR increases the similarity for PDD as well as for WEST for noise levels from 0.016, respectively 0.025 on. Here, the noise level is defined as 1/SNR (0.025 corresponds with SNR = 40, which is a typical value for in vivo diffusion data).

Fig. 2 shows the DRFT result of the body of the corpus callosum. The width of the streamtubes is proportional to m_d and the transparency encodes the number of temporary tracks around the CM. The less opaque a streamtube is, the less likely it really corresponds with an axonal tract (see arrows on Fig. 2). Also, the fibers are colour-encoded to provide directional information (red represents the left-right orientation, blue the inferior-superior, and green the anterior-posterior orientation).

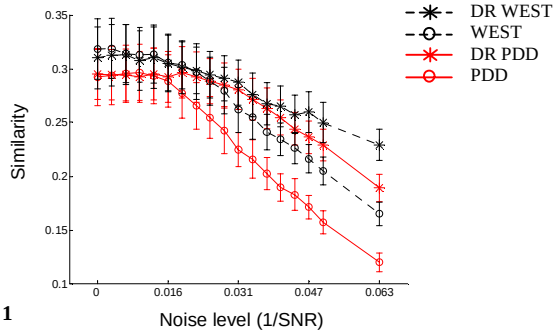

Fig. 1

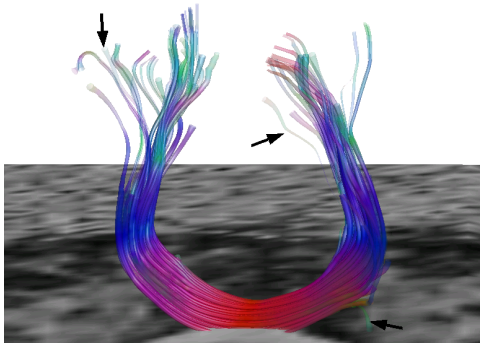

Fig.2

Discussion

Density Regularization proves its value in diminishing the influence of noise on commonly used tractography methods, i.e. it reduces the number of spurious tracts significantly. Moreover, it can stabilize the tracking solutions in regions with very low FA.

Clinicians prefer streamline methods rather than the connectivity maps of probabilistic tractography methods, because the former result in diagnostically valuable 3D (rigidly wired / point-to-point connected) anatomical pathways of the in vivo axonal fibers. With the DRFT technique, we can offer both 3D anatomical tracts and an estimate of probability along each tract. Finally, our proposed technique can be extended to allow fiber branching and crossing.

References

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