In Vivo Quantification of the Accuracy of Estimated Fiber tracts using a Non-Parametric Method

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Introduction

A difficult problem of streamline based fiber tractography is to quantify the precision or repeatability of estimated fiber tracts. One approach used before is to construct the probability map by Monte Carlo simulation through iterating the fiber tracking procedure and taking into account the uncertainty of fiber orientations [1]. Another approach is to use bootstrap resampling for determining confidence intervals of fiber orientation estimates [2]. Both methods are time-consuming and cannot be performed simultaneously with fiber tracking. Here, we propose a computationally efficient statistical method of fiber orientation smoothing with simultaneous quantification of the precision of estimated fiber tract and assessing the probability of connectivity in vivo.

Theory

Our approach is based on Nadaraya-Watson type kernel regression estimate $\hat{v}(x)$ for a continuous space approximation to the orientation vector field $v(x)$ of the tracking propagation,

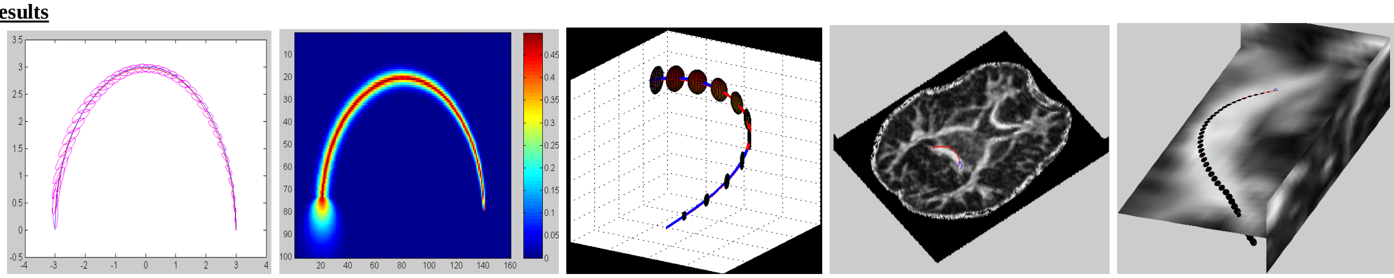
$$\hat{v}(x) = \frac{1}{nh^d} \sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right) v_i \ ,$$

where d is the dimension of measurement data space (d=3 for DT-MRI data), h is the bandwidth or smoothing parameter, n is the total number of observation couples (x_i, v_i) in an area of interest, and $K(x)$ is a kernel function, which integrates to one. The estimated fiber path $\hat{x}(t)$ is obtained by using the $\hat{v}(x)$ in a standard streamline tracking algorithm. In [3], the properties of the stochastic process $\hat{x}(t)$ have been studied in detail. In particular, under some conditions on the orientation of the vector field v, on the kernel K and the bandwidth parameter h, it was proved that the deviation sequence of estimated fiber paths $\hat{x}(t) - x(t), 0 \le t \le T$ converges weakly to a Gaussian process $\eta(t)$. It has mean zero and covariance function $c(t) = c(t,t)$ that depends on the orientation vector field v, the underlying noise covariance and the kernel estimator we are using. This property allows us to perform fiber tracking with simultaneous evaluation of tracking procedure by computing the error covariance $c(t)$. As described in [3], we also find that the distribution of distances between a given point a and the estimated trajectory $\hat{x}(t)$ is asymptotically normal with mean zero and variance $\sigma^2 = 4(x(\tau) - a)^* c(\tau)(x(\tau) - a)$. Here, $x(\tau)$ is the only point on the true trajectory $x(t)$ where the minimal distance is attained. Therefore, we can infer the probability of connectivity from a given point to our estimated fiber trajectory easily. For example, we develop a simple statistical test for the hypotheses about a trajectory passing close enough to a given point and construct confidence intervals for the unknown distance.

Methods

The method was tested by synthetic 2D circle trajectory and 3D spiral trajectory. Further analysis was performed on human brain diffusion tensor MRI data acquired on a Siemens 1.5T Sonata system, using a standard diffusion-weighted-EPI sequence (1NEX; 6 gradient orientations; b value=1000 s/mm2, TR= 5s, TE=100ms, slices thickness=2mm, FOV=256).

Results



(a) (b) (c) (d) (e)

Figure (a) shows the 2D visualization of the confidence ellipsoids of estimated fiber trajectory (red one is the estimated trajectory; the blue line is the true, the coordinate of seed point is (3,0)). The size of confidence ellipsoids increases due to the accumulation of uncertainty of fiber orientations. The p-values of hypothesis testing of connectivity from any given point in the 2D plane to our estimated trajectory are shown in figure (b). The map of this type can be viewed as a simple tool allowing one to assess connectivity likelihoods between points of interest and the fiber tract. Further, visualization of the 3D confidence ellipsoids of an estimated 3D spiral trajectory is shown in figure (c). Using in vivo human MRI data, we presented a single estimated fiber trajectory using our proposed tracking method in figure (d). The blue point indicates the starting seed point. Figure (e) shows the visualization of 3D confidence ellipsoids of our tracking procedure.

Conclusions

In this study, we have reported a novel method for quantifying the accuracy of tracking procedure simultaneously with smoothing of noise. Results demonstrate that the proposed method is feasible and efficient. Up to our best knowledge, this is the first method of simultaneous tracking of fiber path and its error matrix based on rigorous mathematical analysis of the problem. Unlike some other methods based on intensive Monte Carlo simulation, this method is not time consuming.

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Reference

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