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Stability metrics for optic radiation tractography: Towards damage prediction after resective surgery

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HIGHLIGHTS

- The alignment of streamlines is quantified by fiber-to-bundle coherence measures.
- Reliable ML-TP distance measurement by removal of spurious (deviating) streamlines.
- Parameter estimation to remove spurious streamlines and to retain the Meyer's loop.
- The validity of ML-TP distance is estimated by pre and postoperative OR comparisons.
- The stability metrics are promising to relate OR damage to a visual field deficit.

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ABSTRACT

Background: An accurate delineation of the optic radiation (OR) using diffusion MR tractography may reduce the risk of a visual field deficit after temporal lobe resection. However, tractography is prone to generate spurious streamlines, which deviate strongly from neighboring streamlines and hinder a reliable distance measurement between the temporal pole and the Meyer's loop (ML-TP distance).

New method: Stability metrics are introduced for the automated removal of spurious streamlines near the Meyer's loop. Firstly, fiber-to-bundle coherence (FBC) measures can identify spurious streamlines by estimating their alignment with the surrounding streamline bundle. Secondly, robust threshold selection removes spurious streamlines while preventing an underestimation of the extent of the Meyer's loop. Standardized parameter selection is realized through test–retest evaluation of the variability in ML-TP distance.

Results: The variability in ML-TP distance after parameter selection was below 2 mm for each of the healthy volunteers studied ($N = 8$). The importance of the stability metrics is illustrated for epilepsy surgery candidates ($N = 3$) for whom the damage to the Meyer's loop was evaluated by comparing the pre- and post-operative OR reconstruction. The difference between predicted and observed damage is in the order of a few millimeters, which is the error in measured ML-TP distance.

Comparison with existing method(s): The stability metrics are a novel method for the robust estimate of the ML-TP distance.

Conclusions: The stability metrics are a promising tool for clinical trial studies, in which the damage to the OR can be related to the visual field deficit that may occur after epilepsy surgery.

1. Introduction

With diffusion tensor imaging (DTI) the morphology of brain tissue, and especially the white matter fiber bundles, can be investigated in vivo (Mori, 2007), offering new possibilities for the evaluation of brain disorders and preoperative counseling. The optic radiation (OR) is a collection of white matter fiber bundles

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which carries visual information from the thalamus to the visual cortex (Rubino et al., 2005). Numerous studies (Yogarajah et al., 2009; Taoka et al., 2005; Chen et al., 2009; Winston et al., 2012; Borius et al., 2014; James et al., 2015) have accomplished to reconstruct the OR with DTI, by tracking pathways between the lateral geniculate nucleus (LGN) and the primary visual cortex. In the curved region of the OR, configurations with multiple fiber orientations appear, such as crossings, because white matter tracts of the temporal stem intermingle with the fibers of the Meyer's loop (Kier et al., 2004). Therefore, it is especially challenging to reconstruct the Meyer's loop, which is the most vulnerable bundle of the OR in case of surgical treatment of epilepsy in which part of the temporal lobe is removed (James et al., 2015). However, a limitation of DTI is that it can extract only a single fiber direction from the diffusion MRI data.

With the advent of multi-fiber diffusion models it has become possible to describe regions of crossing fibers such as the highly curved Meyer's loop. Tractography based on constrained spherical deconvolution (CSD) (Tournier et al., 2007; Descoteaux et al., 2009) has been shown to have good fiber detection rates (Wilkins et al., 2015) and has been applied in several studies to reconstruct the OR (Lim et al., 2015; Martínez-Heras et al., 2015). Furthermore, probabilistic tractography is considered superior in comparison to deterministic tractography for resolving the problem of crossing fibers in the Meyer's loop (Lilja and Nilsson, 2015). The probabilistic tracking results between the LGN and the visual cortex for a healthy volunteer are illustrated in Fig. 1. The tracking results are shown in a composite image along with other brain structures such as the ventricular system.

However, a common occurrence in tractograms obtained from probabilistic tractography are spurious (deviating) streamlines. Spurious streamlines are by definition not well-aligned with neighboring streamlines and may hinder the measurement of the distance between the temporal pole to the tip of the Meyer's loop (ML-TP distance). An accurate measurement of the ML-TP distance is required for estimating the potential damage to the OR after temporal lobe resection (TLR). Methods have been proposed for the identification and removal of spurious streamlines, for example based on outlier detection (Yeatman et al., 2012; Martínez-Heras et al., 2015; Khatami et al., 2016), based on the prediction of diffusion measurements by whole-brain connectomics (Pestilli et al., 2014), or based on the uncertainty in the main eigenvector of the diffusion tensor (Parker et al., 2003). Most of these methods for reducing spurious streamlines are based on density estimation in $\mathbb{R}^3$. In contrast, in the current study fiber-to-bundle coherence (FBC) tractometry measures are employed that are based on density estimation in the space of positions and orientations $\mathbb{R}^3 \times S^2$. The stability metrics introduced in this study are based on the FBC measures. These metrics provide a reliable OR reconstruction that is robust under stochastic realizations of probabilistic tractography. To achieve a reliable reconstruction of the full extent of the Meyer's loop, an appropriate selection of streamlines is required such that spurious streamlines are removed while preserving streamlines that are anatomically more likely to exist. For this purpose the FBC parameter ϵ is estimated based on the measured variability in ML-TP distance. Here we respect an a-priori constraint on the maximal ML-TP distance variability for a test–retest procedure on streamline tracking and determine the corresponding minimal threshold $\epsilon_{\text{selected}}$ on the FBC measures. This threshold removes a minimal amount of spurious streamlines while allowing for a stable estimation of the ML-TP distance.

In the current study the validity of the distance measurements is evaluated based on pre- and post-operative comparisons of the reconstructed OR of patients who underwent a TLR. It is investigated whether it is feasible to assess pre-operatively for each individual patient the potential damage to the OR as an adverse event of the planned TLR. The deviation between the prediction of the damage to the OR and the measured damage in a post-operative image is compared, giving an indication of the overall error in distance measurement.

The main contributions of this paper are:

- Quantification of spurious streamlines. We provide FBC measures that quantify how well-aligned a streamline is with respect to neighboring streamlines.
- Stability metrics for the standardized removal of spurious streamlines near the anterior tip of the Meyer's loop.
- Robust estimation of the variability in ML-TP distance by a test–retest evaluation.
- Demonstration of the importance of the FBC measures by retrospective prediction of the damage to the OR based on pre- and post-operative reconstructions of the OR of epilepsy surgery candidates.

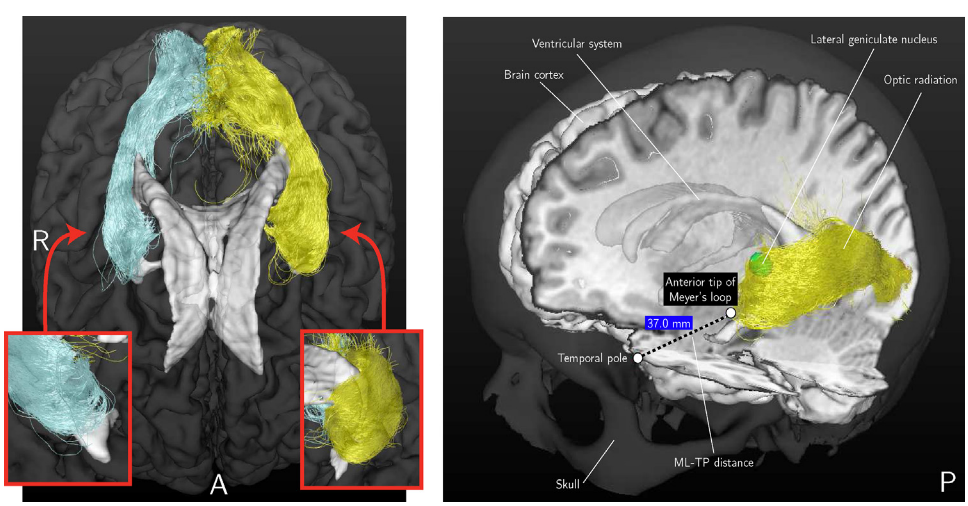

Fig. 1. Left: An example of the reconstruction result of the OR using probabilistic tractography from an axial view. As inserts, close-ups are shown of the anterior tips of the reconstructions of the OR from a coronal view. Right: The tracking results are shown for the same volunteer in a composite image along with other brain structures such as the ventricular system. The ML-TP distance measurement is indicated.