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Prediction of visual field deficits by diffusion tensor imaging in temporal lobe epilepsy surgery

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ABSTRACT

Visual field deficits due to optic radiation injury are a common complication of temporal lobectomy in epilepsy surgery. In this prospective study, diffusion tensor imaging (DTI) based fiber tracking was performed on 48 patients who had temporal lobectomy for pharmaco-resistant epilepsy. Pre- and intra-operative DTI based fiber tracking was used to visualize the optic radiation and to predict the post-operative visual field defects. The course of the optic radiation could be successfully reconstructed by DTI based fiber tracking. There was a significant correlation between the fiber tracking estimation and the outcome of visual field deficits after surgery. The Receiver Operating Characteristic (ROC) curve analysis confirmed the accuracy and validity of prediction of the post-operative visual field deficits comparing pre- and intra-operative fiber tracking results. Intra-operative visualization of the optic radiation may help in avoiding post-operative visual field deficits.

Introduction

Visual field defects (VFDs) due to optic radiation (OR) injury are among the commonest complications after anterior temporal lobectomy for temporal lobe epilepsy (Anderson et al., 1989; Falconer and Wilson, 1958; Hughes et al., 1999; Krolak-Salmon et al., 2000; Wieshmann et al., 1999). Typically, VFDs occur in the superior homonymous field contralateral to the resection and are due to disruption of the OR, especially the anterior bundle, which is also known as Meyer's loop.

Meyer's loop is the most anterior portion of the optic radiation. The fibers of Meyer's loop project from the lateral geniculate body (LGB), running anteriorly across the superior aspect of the anterior tip of the lateral ventricle's temporal horn before making a sharp turn to join the dorsal bundle fibers of the optic radiation in their course towards the calcarine cortex (Choi et al., 2006; Rubino et al., 2005). Meyer's loop transmits visual information from the contralateral superior field of both eyes, and damage to its fibers is one cause of a homonymous superior quadrantanopia (Jacobson, 1997). Estimates of quadrantanopia complicating temporal lobectomy range from 50–70% (Katz et al., 1989; Marino and Rasmussen, 1968; Tecoma et al., 1993) to 90–100% (Bjork and Kugelberg, 1957; Falconer and Wilson, 1958; Hughes et al., 1999).

Although many studies have been done to explore the anatomy of Meyer's loop, there still has been considerable disagreement on the location, course, and anatomy of Meyer's loop in human beings. For example, the anterior limit of the Meyer's loop has not been well localized. It has been estimated at anywhere from 20 to 60 mm posterior of the temporal pole, with a tendency to lower estimates in more recent studies (Krolak-Salmon et al., 2000; Nilsson et al., 2004). There is also controversy on the intersubject variability, even on the intrasubject hemispheric asymmetries in Meyer's loop (Ebeling and Reulen, 1988). As a result, so far to now, the occurrence and extent of a postoperative VFD cannot be accurately predicted by conventional imaging methods or by measuring the extent of the resection.

Diffusion tensor imaging (DTI) is a MRI technique that evaluates brain structure by measuring tissue water diffusion in 3-dimensional (3-D) space (Pierpaoli et al., 1996). It is based on the general principle that diffusion is directed by the anatomical microstructure, i.e. by white matter (WM) fibers (Melhem et al., 2002; Mori et al., 2002; Mori and Van Zijl, 2002; Wiegell et al., 2000). Fiber tracking (FT), also known as “tractography”, allows to non-invasively visualize the course of major white matter tracts based on DTI technique (Basser et al., 2000; Conturo et al., 1999; Lazar et al., 2006; Lazar et al., 2003; Mori et al., 1999; Mori et al., 2002). It can provide information about the course, the displacement, or interruption of white matter tracts. Fiber tracts are estimated by FT with algorithms that detect long-range patterns of continuity in the diffusion tensor field. Multiple studies have demonstrated that FT can reconstruct the major WM fiber structures in the healthy brain (Mori et al., 2002). However, to date, the role of DTI based FT in detection of the optic radiation, including Meyer's loop, has not yet been well addressed. Only a few

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studies with very small cohorts have demonstrated that DTI based FT can reconstruct the major fiber structures of the optic radiation (Powell et al., 2005; Yamamoto et al., 2005). On the other hand, some studies correlating clinical outcome data have recently questioned the accuracy and validity of DTI based FT depicting the major WM tracts (Kinoshita et al., 2005).

In a prospective study we sought to relate the status of Meyer's loop, assessed by pre- and intra-operative DTI based FT, to the extent of VFD following anterior temporal lobectomy. By doing this, we try to determine changes in the size and course of Meyer's loop due to surgical resection, and to address first, whether DTI based FT can precisely depict Meyer's loop; second, if DTI based tractography can accurately predict the resection effects on the visual field; and third, what can be the best strategy to minimize the injury of Meyer's loop during anterior temporal lobectomy?

Materials and methods

Patients

Our study consecutively enrolled 48 patients with pharmacoresistant temporal lobe epilepsy and they all underwent standard tailored anterior temporal lobectomy from January 2003 to May 2007. Conventional anatomical MRI and DTI data were prospectively collected. All patients had both pre- and intra-operative MR imaging and pre- and post-operative visual field examination. We excluded those patients with other ophthalmic or neurological causes of visual loss. Of the 48 patients, 25 had left- and 23 had right-sided resections. Average age of the patients in our study cohort was 35.4 years (SD 12.5, range 8–59 years), with no significant difference between right and left lobectomy groups ($P=0.14$). The local ethical committee of the University Erlangen-Nuremberg approved intra-operative MRI, and signed informed consent was provided by all patients or appropriate family members.

Conventional MR imaging and diffusion tensor imaging (DTI)

Both pre- and intra-operative MR imaging were performed on a 1.5T Siemens Sonata scanner (Siemens Healthcare, Erlangen, Germany) with the same protocol. Details of the intra-operative MRI setting are published (Nimsky et al., 2005; Nimsky et al., 2006a,b). A T1-weighted three-dimensional (3-D) magnetization prepared rapid acquisition gradient echo (MPRAGE) sequence was measured with an echo time (TE) of 4.38 ms, repetition time (TR) of 2020 ms, matrix size of 256×256, field of view (FOV) of 250×250 mm, slice thickness of 1 mm, and slab of 16 cm. T2-weighted images (TE 98 ms, TR 6490 ms, matrix size 512×307, FOV 230×183 mm, slice thickness 3 mm) were scanned as well. Intra-operative scans were performed immediately after anterior temporal lobectomy, prior to head closure.

For DTI we applied a single-shot spin-echo diffusion-weighted echo planar imaging (EPI) sequence (TE 86 ms, TR 9200 ms, matrix size 128×128, FOV 240 mm, slice thickness 1.9 mm, bandwidth 1502 Hz/Px, using b values of 0 and 1000 s/mm^2, 60 slices, no intersection gap, measurement time 5 min 31 s at 5 averages) for DTI. This sequence is based on a balanced diffusion gradient design which strongly minimizes eddy-current artifacts compared to a single-refocused design. One image without diffusion weighting ($b=0$ s/mm^2) and six diffusion-weighted images were obtained with the diffusion-encoding gradients directed along the following axes (±1, 1, 0), (±1, 0, 1), and (0, 1, ±1).

Fiber tracking (FT)

For reconstruction and visualization of the fiber tracts, we used the “Fiber Tracking” module of the navigation planning software iPlan 2.5 (BrainLab, Feldkirchen, Germany). For this purpose, we implemented a tracking algorithm based on a tensor deflection algorithm (Nimsky et al., 2006a,b). Fiber tracking was performed by the first author blinded to the results of the patient's ophthalmological evaluation.

Before tracking is initiated, the user can adjust the FA threshold and the minimum fiber length (stop criteria). Our default FA threshold is 0.15 and the minimum fiber length is 50 mm. Tract seeding is performed by defining a rectangular volume of interest (VOI) either in the FA maps or in the co-registered standard anatomical datasets. We used a multi-VOI algorithm for the fiber tracking of the optic radiation. For the anterior bundle of the optic radiation (Meyer's Loop), VOI 1 was placed on the lateral geniculate body (LGB) on the resection side and VOI 2 was placed at the level of the lower lip of the visual occipital cortex (calcarine cortex) on the same side. We identified the LGB by selecting the axial slice at the level of the transition from the posterior limb of the internal capsule to the cerebral peduncle. At this level, the LGB is visible posterolateral to the peduncles.

For the rest part of optic radiation (central and posterior bundle), VOI 1 was placed on the LGB on the resection side and VOI 2 was placed at the level of the middle and upper lip of the visual occipital cortex on the same side.

Fiber tracts which passed through both VOIs were the final tracts of interest. The final result of the tracking calculation is a parametric display of fibers, which are represented as streamlines, using the standard direction color encoding: left–right oriented fibers are displayed in red, anterior–posterior in green, and craniocaudal in blue, with all other orientations represented by a mixture of these colors (Pajevic and Pierpaoli, 2000; Pierpaoli et al., 1996).

After selecting the appropriate fiber bundle, a 3-D object is generated automatically by wrapping neighboring fibers with a hull. The closing lines around all fibers from all slices together result in the 3-D object. The 3-D object is generated in the 3-D space of one of the regular MRI datasets, such as the MPRAGE dataset, which has a higher resolution than the DTI data, so that in every second slice of the high-resolution dataset, the wrapping contours are interpolated, resulting in a smoother surface of the 3-D object. The time required to process the DTI data and to acquire the preliminary fiber-tracking images was approximately 15 min.

The distance between the anterior tip of Meyer's loop and the ipsilateral temporal pole was measured at the level of midbrain on the axial plane. It was compared with published measurements obtained by previous studies of the optic radiation. The width of Meyer's loop at the resection site was also measured, both pre-operatively and intra-operatively, so that the preserve ratio of Meyer's loop (post-operative width/pre-operative width) could be calculated and recorded. The injury fraction of the Meyer's loop (1-preserve ratio) was also calculated.

For the evaluation of Meyer's loop injury, a five-point injury score was defined to reflect the DTI based FT findings: 1, definitely negative injury (preserve ratio$\geq$80%); 2, probably negative (80%$>$preserve ratio$\geq$60%); 3, indeterminate (60%$>$preserve ratio$\geq$40%); 4, probably positive (40%$>$ preserve ratio$\geq$20%); 5, definitely positive (preserve ratio$<$20%).

Brain shift evaluation

After rigid registration of the pre-operative and intra-operative optic radiation tractography data with the same pre-operative T1 dataset, we measured the shifting distance of the fiber tracts, both vertically and horizontally at the resection site. To evaluate the maximum extent of shifting, the inner borders of the reconstructed optic radiation tracts of the pre- and intraoperative data were segmented. Then, the maximum distance between the corresponding pre- and intraoperative contours was measured. According to the direction of shifting, which was referred to the craniotomy opening, positive or negative values were assigned: horizontally, positive for a movement towards the surface (i.e., swelling), negative for inward