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Visualization strategies for major white matter tracts identified by diffusion tensor imaging for intraoperative use

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Abstract. Streamline representation of major fiber tract systems along with high-resolution anatomical data provides a reliable orientation for the neurosurgeon. For direct visualization of these data in the surgical field applying heads-up displays of operating microscopes, wrapping of all streamlines of interest to render an individual object representing the whole fiber bundle is mandatory. Integration of fiber tract data into a neuronavigation setup allows removal of tumors adjacent to eloquent brain areas with low morbidity.

Keywords: Diffusion tensor imaging; Glyph representation; Fiber tracking; Functional neuronavigation; Visualization strategies; Major white matter tracts

1. Introduction

Avoiding postoperative neurological deficits by preserving eloquent brain areas is a major principle in neurosurgery. Cortical eloquent brain areas can be preserved by identification of these areas by methods such as magnetoencephalography and functional magnetic resonance imaging (fMRI) [1–4]. Integration of these data into 3-D anatomical MR datasets allows their representation in the surgical field by using neuronavigation

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systems, that, e.g. use heads-up displays to visualize segmented data. Diffusion tensor imaging (DTI) can be applied for identification of major white matter tracts, such as the pyramidal tract and the optic radiation [5–8]. Different visualization techniques, such as glyph representation and fiber tracking have evolved in the recent years. The aim of this study is to find a suitable method to visualize the course of major white matter tracts during neurosurgical procedures.

2. Methods

Single-shot spin-echo diffusion weighted echo planar imaging on a 1.5-T MR scanner (Magnetom Sonata, Siemens Medical Solutions, Erlangen, Germany) was used for DTI. The sequence parameters are: TE 86 ms, TR 9200 ms, matrix size 128×128, FOV 240 mm, slice thickness 1.9 mm, bandwidth 1502 Hz/Px. A diffusion weighting of 1000 s/mm2 (high *b* value) was used. One null image (low *b* value: 0 s/mm^2) and six diffusion weighted images were obtained with the diffusion-encoding gradients directed along the following axes ($\pm1,1,0$), ($\pm1,0,1$), and ($1,\pm1,0$). The voxel size was $1.9\times1.9\times1.9$ mm; 60 slices with no intersection gap were measured. Applying 5 averages the total DTI measurement required 5 min and 31 s.

Directly after image acquisition, the DTI data could be evaluated with the DTI task card version 1.6× (Magnetic Resonance Center, Massachusetts General Hospital, Boston) on a Siemens scanner using MR software MRease N4_VA21B under syngo VB10I. The diffusion tensor information could then be represented as color-encoded fractional anisotropy (FA) maps, which were generated by mapping the principal eigenvector components into red, green, and blue color channels, weighted by fractional anisotropy. Assuming the patient is lying in supine position and the head is not tilted, then the color mapping defines white matter tracts oriented in an anterior/posterior direction in green, a left/right direction in red, and a superior/inferior direction in blue. Furthermore, 3-D fibertracking was generated applying a knowledge-based multiple-ROI (region of interest) approach with user-defined seed regions. Tracking was initiated in both retro- and orthograde directions according to the direction of the principal eigenvector in each voxel of the ROI. These data could be displayed on a screen in the operating theatre, however only the DTI information was displayed.

For parallel visualization of 3-D MR anatomy along with both glyph and streamline representation of fiber tracts, the DTI data were rigidly registered. To define the coordinate system of the reconstructed fiber tracts, only the B0 images had to be registered with the T1-weighted MPRAGE data (magnetization prepared rapid acquisition gradient echo sequence; TE 4.38 ms, TR 2020 ms, matrix size 256×256, FOV 250 mm, slice thickness 1 mm, slab 16 cm, measurement time 8 min 39 s). The reconstructed fiber tracts were saved in a simple text file listing the coordinates of each individual fiber, which then could be imported by the navigation system (iPlan, BrainLab, Heimstetten, Germany). Since B0 images and the reconstructed fibers had the same coordinate system, the fibers could be displayed in the T1 3-D dataset. For representation in the surgical field, the maximum outline of the fiber tracts was segmented, so that this object wrapping all fibers could be outlined in the surgical field along with other data, such as the tumor contour [9–11].

3. Results and discussion

In over 50 patients, most of them undergoing glioma surgery, DTI data were acquired pre- as well as intraoperatively. The DTI task card integrated in the MR scanner Syngo interface allowed an immediate visualization of the major fiber tracts, so that this information could be displayed during neurosurgical procedures, even if these data were acquired intraoperatively. However, this visualization lacked the parallel display of high-resolution anatomy, so that the direct 'mental' transfer of the course of the fiber tracts to the surgical field depended much on the clinical experience of the individual surgeon.

Glyph representation of the data was only used to define the seed regions for the tracking algorithm. This visualization method may be of some value and interest when displaying the tumor border and comparing this information to other modalities such as MR spectroscopy (Fig. 1).

Fiber tract representation of DTI data was the preferred display mode (Fig. 2). However, the standard display with smoothed streamlines suggested a high accuracy and resolution of the data, which effectively is not provided by the voxel size of 1.9 × 1.9 × 1.9 mm of the actually measured data.

Integration of DTI information into navigational systems, either by registration of the color-encoded FA maps and manual segmentation of the respective fiber tracts by an expert (applied in 16 glioma patients) or by integrating the reconstructed streamlines in the navigational setup ($n = 20$) allowed a direct visualization of the pyramidal tract or the optic radiation in the surgical field. The fiber tract generation and integration into the navigation system needed about 25–30 min in each case. Integrating the reconstructed streamlines in the navigational setup was less time consuming and less user dependent, i.e. less biased than the approach applying the direct registration of color-encoded FA maps. For the visualization in the surgical field, using the heads-up display systems of navigation microscopes a smooth wrapping of all fibers of interest proved to be of major

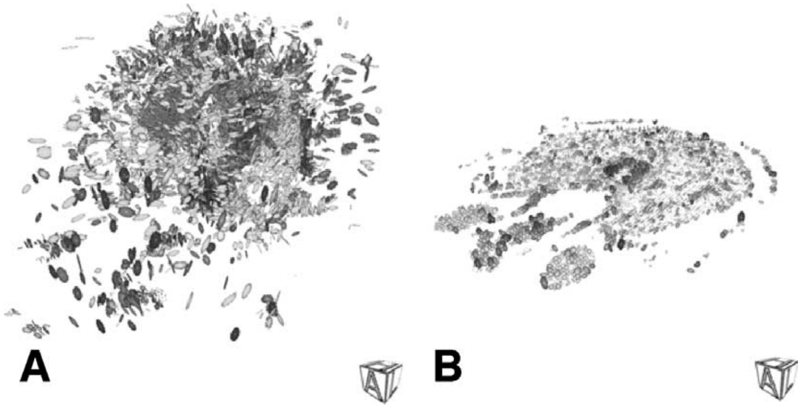

Fig. 1. (A) Glyph representation of the whole brain; only major structures such as the corpus callosum and the pyramidal tract can be identified. (B) Glyph representation in a single slice giving a better overview; this kind of display may be of interest, when DTI data are used to delineate the tumor border.

Fig. 2. Streamline representation of the right pyramidal tract, co-registered with 3-D high-resolution T1-weighted anatomy (a right temporal tumor is segmented), as well as the glyph representation is displayed in the axial cutting plane.

importance, otherwise the displayed structures (contours) in the surgical field could not be related easily to the structures of interest (Fig. 3).

DTI data navigation allowed extended resections with low new postoperative deficits; only in one patient (2.8%) we observed a postoperative neurological deterioration. Additional intraoperative acquisition of DTI data with fiber tract reconstruction visualizes the potential shifting of major white matter tracts. These intraoperative data can be used to compensate for the effects of brain shift. The next step will be the integration of the

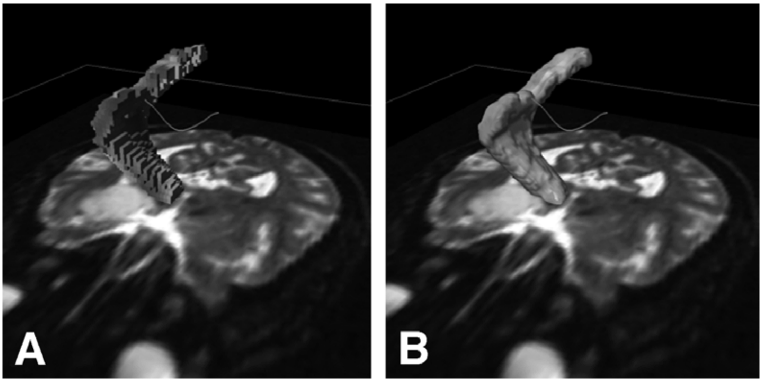

Fig. 3. (A) Wrapping of the streamlines for better intraoperative visualization to display the right pyramidal tract (the same patient as in Fig. 2 with a right temporal glioma), (B) smoothed surface display, so that these data can be injected into the heads-up display of the microscope as one solid object, avoiding confusion by multiple streamlines obstructing the orientation for the surgeon.

tracking algorithms directly in the navigation planning software, so that after image acquisition data from different modalities can be registered and visualized on a common platform allowing intraoperative data representation.

4. Conclusions

Streamline representation of major fiber tract systems along with high-resolution anatomical data provides a reliable orientation for the neurosurgeon. For direct visualization of these data in the surgical field applying heads-up displays of operating microscopes, wrapping of all streamlines of interest to render an individual object representing the whole fiber bundle is mandatory. Integration of fiber tract data into a neuronavigation setup allows removal of tumors adjacent to eloquent brain areas with low morbidity.

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