Reconstruction and Visualization of Major White Matter Tracts

Major white matter tracts are bundles of neuronal fibers connecting the cortical brain areas to deep seated regions and periphery. An example is the pyramidal tract, which is responsible for motor function, or the corpus callosum connecting both brain hemispheres. Their preservation during brain surgery is of major importance, in order to avoid postoperative new neurological deficits, such as impairment of motor function.

Brain surgery, such as the resection of a brain tumor, requires precise surgical planning. For this purpose, information about the location of major white matter tracts is required. *Fig. 1* shows a brain tumor (red) as well as the pyramidal tract in close proximity. The goal is to remove the tumor without impairing motor function. With standard Magnetic Resonance Imaging (MRI) major white matter tracts are hardly distinguishable from surrounding anatomy. Much better results are obtained from Diffusion-Tensor-MRI (DT-MRI), which measures the diffusion characteristics of water molecules in tissue. Since diffusion is anisotropic in areas of strongly aligned microstructure, e.g. major white matter tracts, neuronal pathways can be visualized by DT-MRI.

Processing and visualizing of DT-MRI data is particularly demanding. The first reason is that DT-MRI data has low resolution and exhibits image noise. Secondly, instead of a scalar density value, every data point contains a higher-dimensional tensor that describes the local diffusion characteristics. Since classical visualization techniques are not applicable for tensor data, the eigensystem of the tensor is computed for each data point. The resulting eigenvectors and their eigenvalues serve as basis for different visualization techniques.

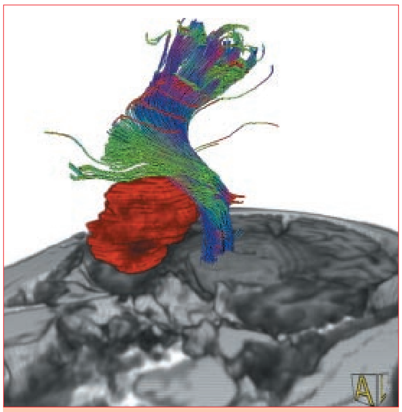

Fig. 1: *Brain tumor (red) with nearby pyramidal tract (color coding according to orientation of the fiber segments in the coordinate system: x-axis: red, y-axis: green, z-axis: blue) with surrounding anatomy* ▪

At the University of Erlangen-Nuremberg, the Collaborative Research Centre (Sonderforschungsbereich) 603 „Model-Based Analysis and Visualization of Complex Scenes and Sensor Data“, funded by the German Research Foundation (Deutsche Forschungsgesellschaft), has been established in 1998. An interdisciplinary subproject between the neurosurgery hospital and the chair for computer graphics is dedicated to the reconstruction and visualization of neuronal pathways. The research is performed at the Neurocenter, an interdisciplinary institution which was established to enable and support close collaboration between engineers, computer scientists, physicians, and natural scientists. Within this research project, the first visualization strategy for a comprehensive representation of the data was the so called tensor-glyph approach *(Fig. 2)*. Glyphs are geometric objects, e.g. cubes or ellipsoids, whose orientation and scaling correspond to the eigenvectors and eigenvalues of the associated tensors. The number of glyphs required for representing an entire dataset is immense, and the number of required ren-

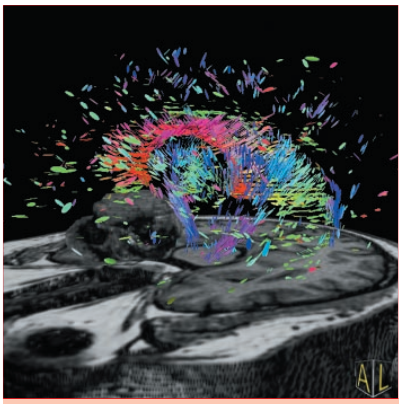

Fig. 2: *Glyph visualization of a DTI dataset* ▪

der primitives, i.e. triangles, is even higher. For this reason, a special approach for the visualization of tensor glyphs was developed which exploits the capabilities of current PC graphics hardware by reducing the geometric load, enabling interactive exploration of the dataset.

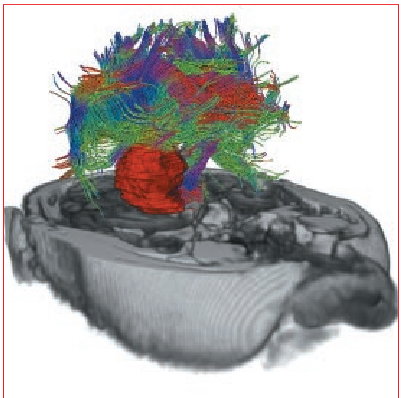

Fig. 3: *Rendering of the neuronal pathways in the whole brain based on fiber tracking, tumor (red)* ▪

Since glyph visualizations are difficult to interpret, alternative visualization approaches known as 'fiber tracking' were implemented. For this purpose, the tensor field is reduced to the field of the major eigenvector, and streamline propagation techniques known from flow visualization are applied. This is accomplished by placing seed points in regions of anisotropic diffusion followed by path integration methods in order to trace the way of particles through the eigenvector field. The resulting streamlines approximate the position and orientation of the underlying white matter structures and can be visualized using line rendering. The reconstructed fibers already provide a good model of the neuronal pathways and are used for diagnosis and preoperative planning *(Fig. 3)*.

However, for surgical planning and intraoperative visualization involving the OR microscope, this kind of visualization is not appropriate. In addition to the details depicted with fiber tracking, the border between neuronal pathways and surrounding tissue has to be visualized. Based on these

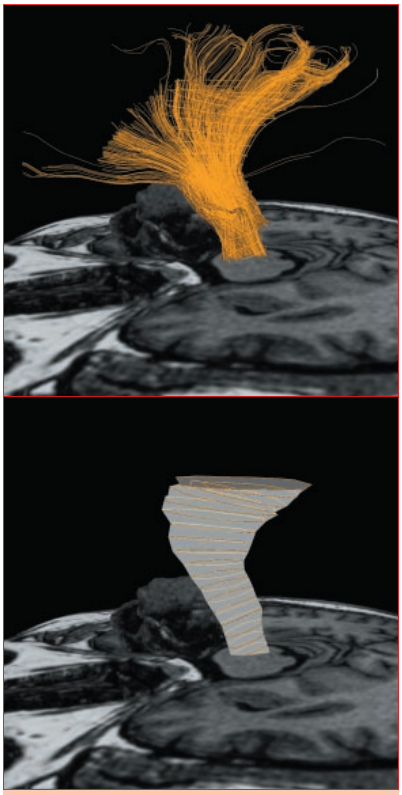

Fig. 4: *Clustering of the fibers of one tract (top) and the corresponding hull (bottom)* ▪

requirements, a clustering approach was implemented in order to extract separate tract systems attributed to specific function. Additionally, hulls were generated which provide a clear visualization for treatment planning *(Fig. 4)*. In the context of an 'augmented reality' approach, the hulls are also suited for direct visualization in the OR microscope.

Another problem for clinical application of DT-MRI data arises from image distortions which result from susceptibility artifacts encountered for the EPI sequences applied in DT-MRI. Correction of these distortions is achieved by non-rigid registration with undistorted anatomical MR data. The high computational cost of non-rigid registration was reduced by exploiting the computing power of modern graphics cards, resulting in a speed up of computing times. This technique enables a correct fusion of major fiber tract systems with anatomical data used for neuronavigation. As a result, it is possible to superimpose the contours of important fiber tracts on the microscope view *(Fig. 5)*.

Another important area of current research is the localization of activated cortical areas (i.e. speech areas) using magnetoencephalography (MEG) and functional MRI (fMRI), as well as the analysis of neuronal connectivity between the identified functional regions. For connectivity analysis, a novel approach based on pathfinding has been developed. Contrary to fiber tracking, the approach takes advantage of the whole local diffusion tensor. In order to establish a connection between two functional regions, a cost function is evaluated which provides the most probable path *(Fig. 6)*.

All presented approaches were integrated into the software platform MEDALYVIS *(Fig.7)* which

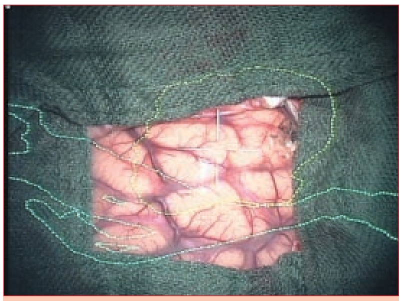

Fig. 5: *Contours of eloquent structures superimposed on the view of the OR microscope.* ▪

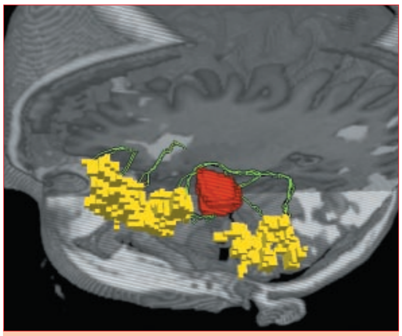

Fig. 6: *Connectivity analysis between speech areas (yellow), tumor (red)* ■

has been developed at the Neurocenter and the Computer Graphics Group. As a result, different reconstruction and visualization approaches can be compared and used for clinical evaluation. Future prospects of the project comprise the visualization of neuronal pathways for intra-operative application in arbitrary pathology, as well as the reconstruction of small fiber tracts in peripheral regions of the brain. The reconstruction and visualization methods currently available already are an important step towards safe resection near functional regions. These techniques support planning in neurosurgery and help to minimize the risk of post-operative neurological deficits. ■

Literature

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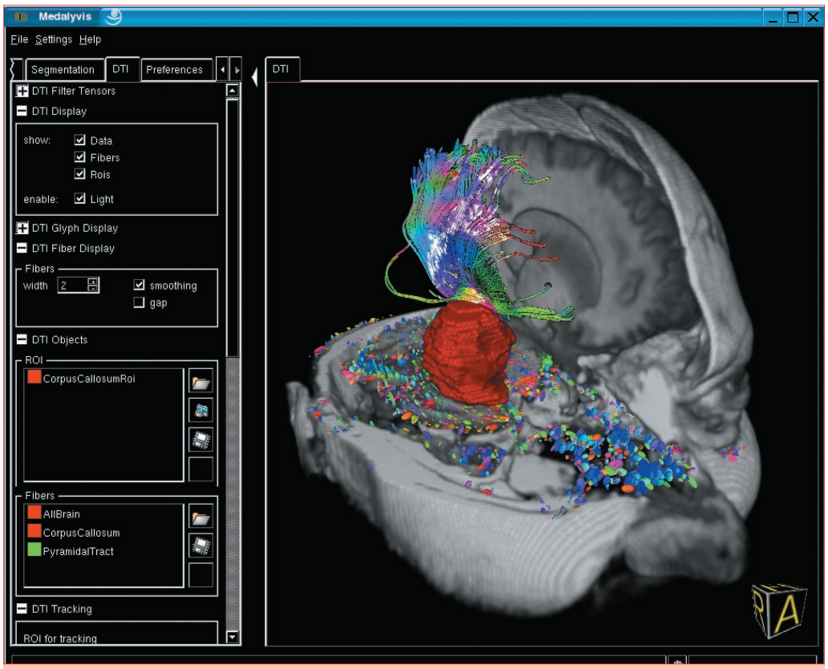

Fig. 7: *User interface of the software platform MEDALYVIS for the analysis and visualization of medical images of different modalities* ■

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