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Multimodal Visualizations for Pre-Operative Neurosurgical Planning

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Abstract: In pre-operative neurosurgical planning, the visualization of structures at risk within their anatomical context is beneficial to answer clinical questions, such as the spatial and functional relation of structures or the definition of the incision point for the intervention. Therefore, we present a multimodal visualization approach, *Cavity Slicing*, which is inspired by focus-context rendering and intuitively reveals inner structures of the brain. Additionally, enhanced visualization techniques are introduced and applied to essential structures for neurosurgery planning, such as a fiber filtering approach and access path visualization to aid the surgeon in terms of diagnosis and pre-operative planning.

1 Introduction

In the living brain, vital structures include functional areas as well as fiber bundles connecting these areas. If pathologies, for example a tumor, are present and derogate essential functionalities, neurosurgical treatment is needed. Neurosurgeries are tailored to the patient specific anatomy and pathology. Hence, within an individual pre-operative planning phase the most adequate access path to a lesion is defined. This is mandatory with respect to deep-seated structures or lesions close to essential white matter tracts, such as the corticospinal tract or related functional activation zones. It is crucial to minimize the damage of these structures at risk.

The visualization of patient-specific anatomical, functional and pathological structures can enhance the treatment planning of surgical interventions. Therefore, multiple modalities have to be acquired. In neurosurgery, major acquisitions include *fMRI* (functional magnetic resonance imaging) to define activation areas; *DTI* (diffusion tensor imaging) to reconstruct neuronal pathways and T_1-*weighted* and T_2-*weighted* MRI (magnetic resonance imaging) sequences for anatomical information. Multimodal approaches combine these datasets into one visual representation hence, embedding properties of the brain in their anatomical context and thereby offering a new insight into pre-operative imaging.

Computer graphics techniques such as visual enhancements, annotations and access path visualizations can support the surgeon in identifying risk-structures and therefore improve the planning phase. An enhanced visualization approach, combining several modalities for pre-operative neurosurgical planning is a challenging task. In this paper, we make the following contributions:

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- With *Cavity Slicing* we provide an intuitive exploration method for multimodal data. Potential adjustments to the slicing include changes of the cutting geometry itself or the position, which is either view-dependent or view-independent. Therefore, structures can be visualized within the surrounding tissue. Considering the slicing geometry as the access path and adjusting the cutting depth towards the tumor, enables the examination of structures lying along the path in an intuitive way.
- We apply the general approach of *fiber filtering* to extract meaningful subsets. Fiber tracts associated with specific activation areas, the tumor or those crossing the access path are extracted.
- We enhance the visualization and evaluation of access paths to provide a better understanding of attributes such as length and spatial arrangement. We used computer graphics techniques to encode the distance of structures to the path. The evaluation of different access paths against each other is simplified, since an iteration through defined paths is possible with adaptive distance encodings.
- We propose a workflow for intervention planning using the introduced methods.

We implemented our prototype with the rapid prototyping system MeVisLab[1] Version 2.1 which includes extendable image processing and visualization modules. For *DTI* visualizations and computations we used a DTI add-on. The presented work is based on the IEEE Visualization Contest 2010[2] submission by the University of Koblenz.

This paper is organized as follows: Section 2 presents some related work in the field of multimodal visualization. Medical data as well as preprocessing is introduced in Section 3. The visualization of brain properties will be discussed in Section 4, a multimodal visualization approach in Section 5, followed by the evaluation of potential risk-structures (Section 6) and the interaction with our system for the actual intervention planning (Section 7). In addition, we suggest a workflow for finding an appropriate access path with our prototype (Section 8). Section 9 shows the results of our work and Section 10 the conclusion and future work.

2 Related Work

Pre-operative planning in neurosurgery is an active field of research [SFJ$^+$05, BBM$^+$07, SJF$^+$00, RRRP08]. In multimodal visualizations, one powerful way to highlight inner structures are cutting techniques. Beyer et al. [BHWB07] introduce a planning application including a multi-volume raycasting approach. The presented approach applies a view-dependent skull peeling to remove parts of the volume obscuring structures of interest. Clipping tools defining a cut-out geometry are a common technique to extract inner structures [MFOF02, JSV$^+$09]. The identification of fiber pathways connecting functional

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[1] http://www.mevislab.de/, last accessed July 3, 2011
[2] http://viscontest.sdsc.edu/2010/, last accessed July 3, 2011

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areas is crucial in neurosurgical planning. Talos et al. [TDW$^+$03] examined the combination of DTI and *fMRI* data and thereby correlated fiber tracts to cortical areas. Several approaches for a combined visualization exist [HBT$^+$05, KSV$^+$10]. Fiber selection methods [BBP$^+$05, BBM$^+$07, MGBN10] result in fiber subsets, crossing a specific region. The winning entry of the IEEE visualization contest 2010 [DPL$^+$10] introduced a surgery planning tool including an exploration and an in-detail inspection step, similar to the steps presented in this work. In the exploration section, the surgeon can examine the multimodal data in a 3D context view and define an initial access path. The authors introduced a so called tumor map, which reveals the distances of risk-structures to the tumor. In the second part the chosen access path and the related structures can be examined in more detail. Another honorable mention submission of the IEEE visualization contest 2010 [BWR$^+$10] presented a planning approach including distance measurements between the tumor and structures at risk as well as focus and context rendering approaches to facilitate orientation.

3 Medical Data

In neurosurgical planning, different acquisition schemes represent different structures of interest. Neuro-visualizations have to combine these datasets to meaningful representations. For this research paper, we used data provided in the course of the IEEE Visualization Contest 2010. The given case contains MRI data of a patient with an intra-cerebral metastasis.

3.1 Data Acquisition

Data has been acquired on a Siemens 3T Verio MR scanner. The anatomical scans include a T_1- and T_2-*weighted* MRI with a resolution of 1 mm^3 and size 512×512×176. Additionally, a T_1 contrast enhanced MRI sequence was available, as well as a brain- and tumormask as a segmentation result on the T_1-images. Functional data was acquired through *fMRI* and the performed task was fingertapping. A *t-map* (statistical parametric map) of size 64×64×64 was provided, containing the evaluation of the *fMRI* data. *DTI* data (size: 128×128×72×62) includes one B_0 image followed by 30 diffusion gradient images. Two repetitions were applied with a b-value of 1000.

3.2 Data Preprocessing

The first step in multimodal visualization is the registration of various datasets to achieve a spatial alignment. However, image registration was not focus of this research. The used datasets have been linearly co-registered to the T_1-*weighted* reference dataset by the IEEE contest initiators. In terms of vessel extraction, the basis forms the T_1-*weighted* dataset, where the vascular structures are enhanced by a contrast agent. This dataset is substracted from the T_1 image without contrast enhancement, similar to digital subtraction angiography (DSA). As a result, the vascular structures are highlighted. To exclude neck vessels and focus on larger vessel around the cortex, the substracted image is masked with the enlarged brainmask. For further improvement, the vesselness filter proposed by Sato et al. [SNA$^+$97] is applied. The filter calculates a multi-scale vesselness measure as a function of the Hessian matrix. Each voxel in the output volume indicates how similar the local structure is to a tube. The actual segmentation is performed by a region-growing algorithm. Table 1 gives an overwiew of the steps for vessel segmentation and the computation time.

Preprocessing step	time in seconds
T_1 contrast enhanced substraction	2
Brainmask dilation	103
Vesselness filter	22
Region growing	1

Figure 1: Steps and timing for vessel segmentation.

Neuronal pathways were reconstructed using a fiber tracking implementation of the algorithm, proposed by Lazar et al. [LWT$^+$03].

4 Visualization of Anatomical and Functional Structures

Volume visualizations such as rendering of the T_1, T_2 or the cortex, are performed using a direct volume rendering MeVisLab module, called *GVR* (Giga Voxel Renderer) [LKP06]. Isosurfaces are generated with a marching cubes based approach and internally represented as winged edge meshes. Vessels are colored red and the tumor purple. Activation areas are visualized through both volume and isosurface rendering. Isosurfaces are generated by applying a threshold to the given statistical parametric map (*t-map*) and thereby define core activation areas, colored yellow. Volume rendering of the *t-map* shows extended activation zones. Therefore, the color appearance and the extent depend on the selected transfer function and are defined in the color range from yellow (core activation) to red. This can be considered as an uncertainty visualization for *fMRI*, since one can distinguish between core activation (isosurface) and less intensive activation (volume rendering). Furthermore, it is possible to mark the most relevant activation zones (isosurfaces) for intervention planning. The following measurements and filtering methods are only performed on the selected parts. Fiber filtering aims to extract meaningful subsets out of a whole brain fiber tracking. Subsets are extracted by the application depending on the inquiry or manually by the user. Automatic extractions include: Fibers crossing activation areas or selected subsets, the tumor or the critical region surrounding the tumor as well as the access path. Fig. 2a shows a fiber filtering with the selected core activation area as the structure of interest, Fig. 2b the tumor crossing fibers and a fiber filtering with respect to a selected path is displayed in Fig. 3.

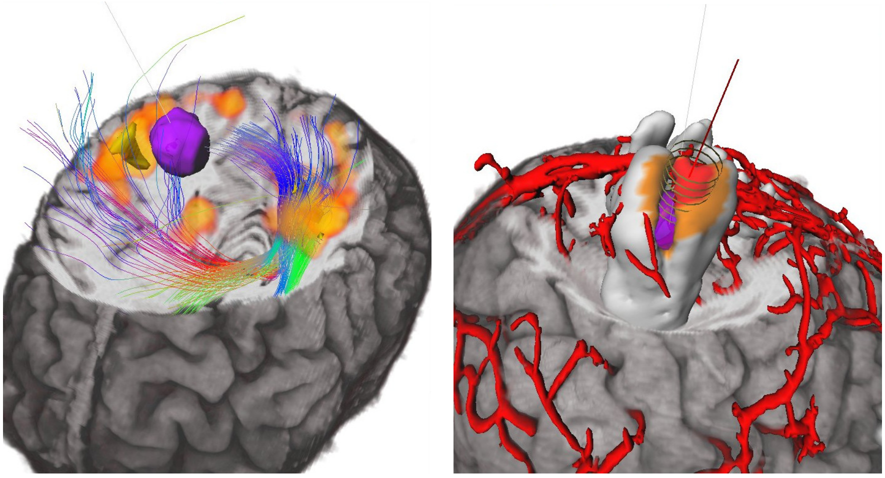
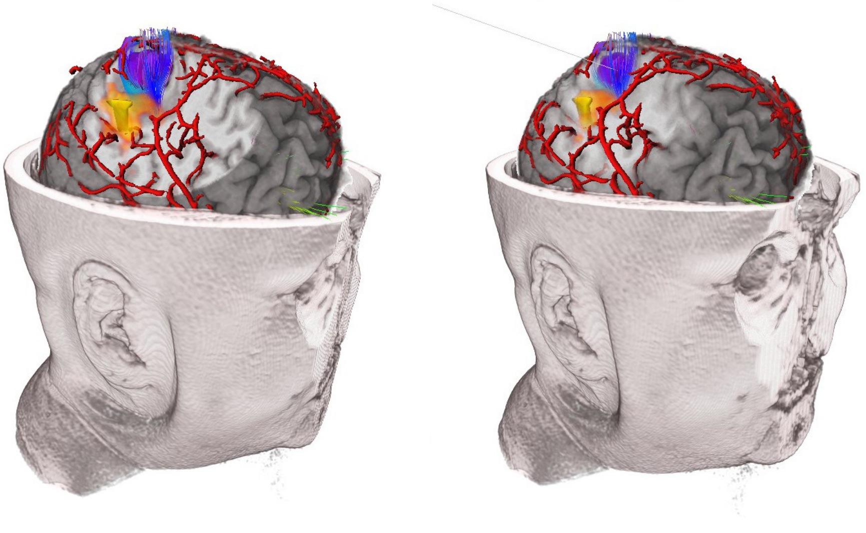

(a) (b)

Figure 2: (2a) Fiber filtering with *fMRI* core activation areas. (2b) Visual distance enhancements: Tumor, vessels and wrapping of path crossing fibers with distance to path color coding.

Visual cluttering is a well-known problem in terms of fiber rendering. Streamlines quickly become difficult to comprehend due to missing depth information and the often overwhelming amount of lines. In addition, single streamlines are sometimes of minor interest in neurosurgical planning [NGH$^+$05]. It was therefore decided to hide this complexity, if desired, using a fiber wrapping approach (Fig. 2b). The wrapping forms a three-dimensional hull around related fibers and provides a more intuitive spatial perception.

5 Multimodal Visualization

In neurosurgical planning, multimodality is crucial, since vital structures of the brain are represented within different datasets. Rieder et al. [RRRP08] cut out a cavity as a clipping geometry, between the POI (point of interest, the tumor center) and the incision point. In our approach we modified this concept in terms of view vector alignment and the shape of the cut-out geometry. We call this method *Cavity Slicing*. The clipping is only applied to the anatomical volume. Therefore, enabled risk-structures between the POI and the skull remain visible. To minimize necessary definitions made by the user, the slicing volume has the following initial settings: The orientation of the clipping geometry is aligned with the view vector, enabling an exploration of structures from each point of view while panning around the head. If an appropriate angle that reveales structures of interest is found, the user can freeze the orientation. By moving the camera slightly, an improved depth perception is achieved: The camera is independent from the clipping orientation and the shape of the slicing geometry becomes comprehensible. Supplementary, the surgeon is able to define the clipping volume in terms of radius, depth and radial smoothness, as shown in Fig. 3.



(a)

(b)

Figure 3: *Cavity Slicing*: Tumor, vessels, tumor crossing fibers, *t-map* volume and core activation areas are visualized. (3a) View-dependent clipping without smoothness. (3b) View-independent clipping with applied smoothness. The gray line represents the orientation of the clipping geometry.

The initial depth is defined by the tumor center, since structures lying behind are of less importance. For further exploration, the depth of the geometry can be changed interactively by the expert. A large radius results in a plane-like clipping of the anatomical volume and is beneficial within the exploration stage, whereas a small radius cuts out only a tube shaped geometry and restricts the visualization to structures lying between the tumor center and its projection to the skull. This can be considered as an access path visualization. The smoothness parameter defines the radial gradient of the clipping geometry. It results in a transparency adjustment of the cut-out region of the anatomical volume. The defined clipping geometry results in a masking volume, which is applied to the anatomical volume using the MeVisLab Giga Voxel Renderer options. The opacity modulation is an implementation of the level of sparseness approach, which was introduced by Viola et al. [VKG04] as a focus and context rendering approach. The proposed method aims at emphasizing important structures covered by less important regions by defining a level of sparseness to each structure. By means of compositing, more important structures are visible through less important ones. Hence, tuning the transparency of regions is one way to visualize the level of sparseness. We consider adjustments to our clipping geometry in general as modifications concerning the importance of the relevant structure.

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6 Risk Structure Evaluation

During a pre-operative planning phase it is essential to identify structures at risk in the following neurosurgical intervention. Functional information and the spatial relation of these structures is vital. Therefore, it is advantageous to gain more information about these structure and their relation. Accurate 3D distance measurements are of major importance in neurosurgical planning tools. In our approach, we enable the computation of the shortest distance from the tumor boundary to a chosen structure at risk, for example, vessels, fiber tracts or activation areas. Furthermore, all minimal distances from the access path to risk structures are calculated. As a result, an arrow is displayed as a visual aid. Moreover, it is possible to compute the shortest distance to a whole structure or just a subselection. The selection can be defined by the user by marking a region on the structure with a lasso tool. Besides distance measurements, we provide two enhanced color codings, directly mapped on the vessels' or wrapped fiber tracts' surface. Color enhancements are implemented using a GLSL shader program. With the first approach, the color of the structure fades to black, depending on the distance to the chosen access path. Parts that are very close to the access path are fully saturated in the respective color and thereby the attention is focused on essential components. The length of the color gradient can be adjusted interactively by the user, allowing for the determination of the range of interest. The second approach uses colors to indicate distance steps from red to yellow (Fig. 2b). Additionally, the exact number, minimum/average/maximum length and fractional anisotropy (FA) of the currently selected fiber set can be visualized. The coloring of fiber sets can be changed to represent the fractional anisotropy value, encoded in grayscale, to highlight the integrity of neuronal pathways (Fig. 4). A FA-value of zero represents low directional information and

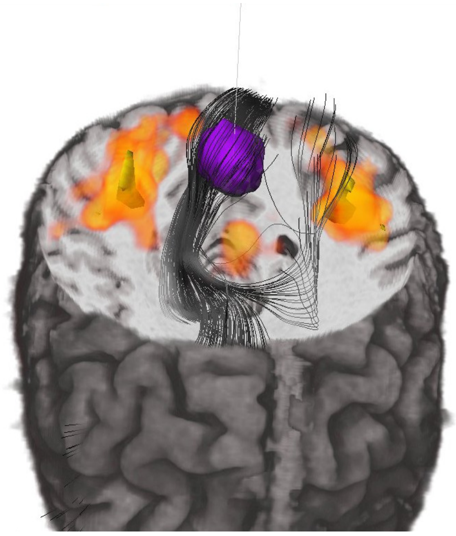

Figure 4: Grayscale color-coding to highlight fiber integrity.

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is encoded in black, whereas a high fractional anisotropy is encoded in white, respectively.

7 Intervention Planning

An access path to the lesion is defined by an incision point on the skull and the center of the tumor. To define the access path, we display the brainmask slightly transparent. Therefore, the user has the idea of the brain's surface in combination with previously defined risk-structures. The incision point for the intervention is defined through a mouse click onto the brainmask.

In conventional planning tools, the path between the lesion and the incision point is represented by a simple line. Disadvantages of this visualization are a weak depth perception and information loss in case the path is hidden by various structures. Therefore, we extend the access path visualization in several ways. Structures lying within an access path present an essential condition for planning a neurosurgical intervention. However, the length is a crucial attribute of a potential path as well. Besides displaying the length of the chosen path in millimeters, we mirror the line representing the path on the head's surface to the outside. More precisely, the line is elongated by the distance from the center of the tumor to the incision point. Both parts are colored red but differ in saturation to indicate the incision point. Thus, the user always has an idea of the length and orientation of the possibly hidden access path. Since it is difficult to notice the spatial orientation of a line in 3D, we wrap a tube around the part lying inside the head. To provide a visual idea of the path length, the tube is divided into a number of rings with a custom separation and radius. Fig. 5 illustrates the path-specific visual enhancements. Additionally, adjustments to the rings can be beneficial in terms of the identification and position of risk-structures. Enlarging the rings reveals adjacent structures that might not be touched during the intervention, for example functional areas.

For evaluation purposes, we enable the surgeon to define markers indicating incision points. All path-related visualizations (distance colorings) and computations (distance measurements, fiber filtering) are automatically adjusted to the path indicated by the selected incision point. As follows, the user can easily switch between the defined paths and compare them against each other.

8 Workflow for Surgery Planning

In the following, we propose an analysis workflow for pre-operative planning using the presented methods.

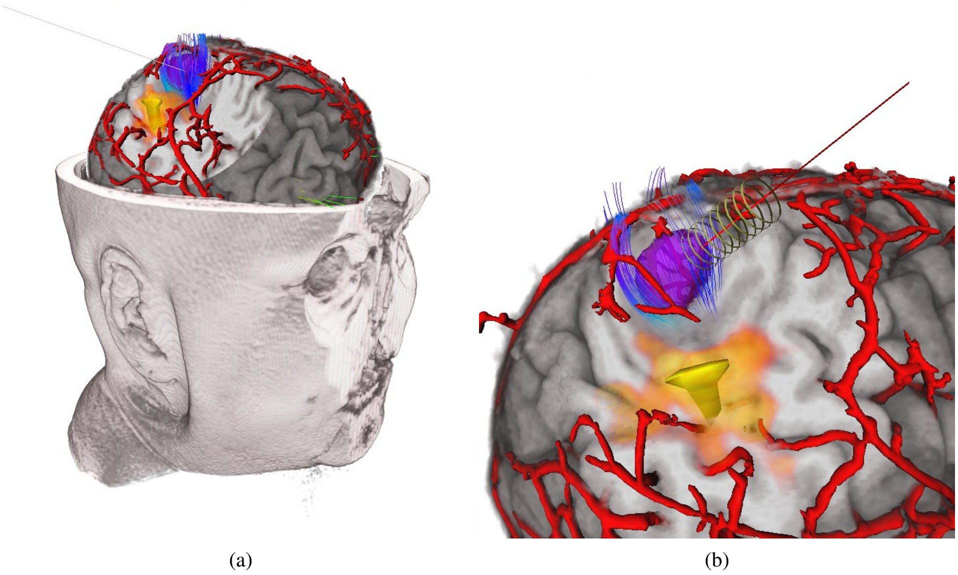

Figure 5: (5a) *Cavity Slicing* is applied to the anatomical volume. Tumor and vessels are displayed. Fiber filtering provides path crossing fibers. (5b) Path visualization: Visual enhancements facilitate the understanding of the spatial position of the path.

8.1 Exploration Stage

The individual patient status can be well inspected in the 3D visualization of the anatomical and the functional structures in the exploration stage. In particular, the location of the lesion is of major importance and anatomic and functional structures have to be examined with respect to their spatial relation. *Cavity Slicing* (view-dependent and view-independent) is especially helpful at this stage, since it reveals structures in their anatomical context. Fiber filtering is beneficial to reveal important fibersubsets, for example those passing *fMRI* activation areas or the lesion. Hence, a precise view on the most important information is given. The exact location of core activation areas through *fMRI* is accompanied with uncertainty. Therefore, functional areas can be extracted through volume renderings of the *t-map* with a user-defined transfer function. DTI representations incorporate uncertainties regarding the integrity of fibers, which are usually not highlighted in visualizations. Enabling the FA-based color coding provides insight into fiber integrity and hence, anatomical and functional properties can be explored regarding specific clinical questions.

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8.2 Surgery Planning Stage

After an initial exploration of the data, the actual surgery planning takes place, defining possible incision points and thereby access paths. Distance measurements can be applied to further enhance the spatial understanding of the data. For example the position of risk-structures with respect to the tumor. Potential infiltrations of vital fiber tracts by the lesion can be detected through fiber filtering and color encodings. To indicate different access paths, labels for the entry point can be defined.

8.3 Evaluation Stage

The defined paths can be examined in the evaluation stage by switching between the markers. Adjustments to the path encompassing rings are a visual aid in evaluating distances of adjacent risk-structures. Distance color encodings on fiber wrappings provide information regarding critical regions during surgery. For path evaluation, the user can adjust the radius and the smoothness of the *Cavity Slicing*. If the user constantly increases the depth of the clipping geometry while passing risk-structures along the way to the lesion, an understanding about the acutal opening is provided. Exploring the data or planning an access path with a new patient dataset inclose to make individual settings, as for example adjusting transfer functions or determining fiber tracking parameters. Therefore, we implemented the possibility of storing presets, in which settings can be made by an assistant and then loaded by the surgeon for further investigation and actual treatment planning. Furthermore, presets are a very convenient way to deal with complicated cases where further expert reports are needed.

9 Results

The stated visualizations run with interactive frame rates. Table 6 provides an overview of the frame rates on a Core2 Duo, 3.16 GHz with 4 GB RAM and an NVIDIA GeForce GTX 285 graphics card. For evaluation purposes, the rendering was rotated by 360 degrees. The viewport size was 512×512. Parts of the presented work were presented in the IEEE Visualization Contest 2010 which targets the field of multimodal visualization for neurosurgical planning. In the course of the review, two neurosurgical experts evaluated our prototype in terms of multimodality, quality of visualization, interaction as well as the clinical value. Summarizing, *Cavity Slicing* seems to pose a real improvement to the current exploration tools for multimodal datasets. Both the viewport dependent clipping and the viewport independent version were considered to be a benefit in neurosurgical planning. The overall clinical value and recommendation was rated to be very good.

Visualization	
T_1: plane slicing, cortex: view-dependent *Cavity Slicing*	15 fps
+ tumor, vessel, tumor crossing fibers	10 fps
+ *fMRI*(core activation, volume rendering of *t-map*)	9 fps
+ wrapped tumor crossing fibers	9 fps
+ smoothed *Cavity Slicing*	9 fps

Figure 6: Frame rates of visualizations in respective views.

10 Conclusion and Future Work

In this paper we presented new exploration approaches for multimodal visualizations with improvements in neurosurgical planning. Additionally, we introduced interaction methods, supporting the surgeon in identifying risk structures and defining an appropriate access path to the lesion. Computer graphics techniques are used to enable multimodal rendering, enhance the appearance of the risk-structures and encoding essential information for surgery planning. We believe that the proposed three-dimensional approaches can pose a real benefit in neurosurgical planning.

Future work will include an integration of more sophisticated fiber visualization, for example streamtubes or illustrative rendering techniques to improve depth perception. In addition, we want to include advanced diffusion visualizations based on Q-Ball reconstruction approaches. These are able to identify more than one diffusion population per voxel and can provide detailed directional information of white matter in challenging regions, like the edema.

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