2010 IEEE Visualization Contest Winner: Interactive Planning for Brain Tumor Resections

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We've developed an intuitive planning system for neurosurgical procedures, using a variety of visualization techniques. In cooperation with our medical partners, we identified a workflow during which the surgeon inspects the tumor and surrounding tissue and specifies and analyzes access paths. To support this workflow, our application prototype utilizes novel as well as best-practice visualization techniques. It won the 2010 IEEE Visualization Contest (see the related sidebar).

The Datasets

All the contest entries employed two state-of-the-art datasets acquired on a Siemens 3T Verio scanner. Each dataset consisted of

- anatomical images consisting of T1-weighted images (which provide high resolution of the anatomy), T1 images with a contrast agent, T2-weighted images (which highlight fluid and pathology), fluid-attenuated inversion recovery (FLAIR), and susceptibility-weighted imaging (SWI); and
- functional or structural images consisting of functional magnetic resonance imaging (fMRI) of a finger-tapping task and diffusion tensor imaging (DTI).

Additionally, all the entries employed postprocessed data such as brain and tumor masks, and a statistical parametric map of the fMRI data. One dataset also contained high-resolution computed tomography (CT) data.

The Clinical Questions

Proposed visualization solutions for the contest had to answer these questions:

- What's the relation between the lesion, functional areas, and white-matter tracts?
- How can you access the lesion most safely?
- How close is the tumor to vital functional areas, such as the visual, language, or motor system?
- What's the distance between the tumor and important fiber bundles related to motor, language, and vision tasks?
- Does the tumor infiltrate or displace any of these tracts?
- To what extent (how radically) can you perform a resection?
- Which arteries or veins lie on the chosen access path?
- Finally, taking into account the technical limitations of the underlying magnetic-resonance measures, an important aspect deals with the certainty with which you can regard algorithmically derived measures. This is especially important for DTI and fMRI. How can you effectively visualize the remaining uncertainty?

Planning Workflow

We identified a two-step workflow. The first step is the initial investigation of the data, combined with an interactive access-path specification. The second step is deeper analysis of the chosen access path and the actual preparation for the surgery. Surgeons

 Published by the IEEE Computer Society

The 2010 IEEE Visualization Contest

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The annual IEEE Visualization Contest presents challenging problems to the research community in the hope of obtaining novel solutions. The contest promotes a problem in a different domain each year by providing data and corresponding scientific queries that can be addressed through visualization. Data format documentation and sample reader programs are available for contestants to validate processing and jump-start their work. The contest has become a widely used repository of well-defined scientific problems with open data. Past and upcoming contest data, questions, and submission archives are available at http://viscontest.sdsc.edu.

The Contest Problem

The 2010 contest's theme was multimodal visualization for neurosurgical planning. The primary challenge in planning neurosurgical interventions is identifying the various structures at risk and understanding how they relate and interact. The most relevant structures are functional areas in the gray matter of the cortex and white-matter fiber tracts connecting different areas. Surgeons must treat both with equal care. Damaging a functional area or white-matter tract will seriously impair the patient. So, neurosurgical planning aims to identify all the structures at risk, their spatial relation to the lesion that's targeted for resection, and a safe access path to that lesion. For more information on the 2010 contest data and questions, see the related sections in the main article.

Evaluation

Contestants had to submit a two-page document describing the visualization and analysis, supplemented by up to 12 images and a video of up to 10 minutes. We received 11 submissions, the most the contest had ever received. Three visualization experts reviewed all submissions; neurosurgical experts reviewed the top nine submissions. They evaluated the submissions on clarity, technical soundness, multimodality, the quality of visualization and interaction, the clinical value, and the depiction of uncertainty.

The Results

The winner was "Preoperative Planning of Brain Tumor Resections" (Stefan Diepenbrock, Jörg-Stefan Praßni, Florian Lindemann, Hans-Werner Bothe, and Timo Ropinski). For more on the winner, see the main article.

Honorable mentions went to

- "An Exploration and Planning Tool for Neurosurgical Intervention" (Diana Röttger, Sandy Engelhardt, Christopher Denter, Burkhard Güssefeld, Annette Hausdörfer, Gerrit Lochmann, Dominik Ospelt, Janine Paschke, QiAn Tao, and Stefan Müller),
- "Neurosurgical Intervention Planning with VolV" (Silvia Born, Daniela Wellein, Peter Rhone, Matthias Pfeifle, Jan Friedrich, and Dirk Bartz), and
- "A Fiber Navigator for Neurosurgical Planning (NeuroPlanningNavigator)" (Olivier Vaillancourt, Gabriel Girard, Arnaud Bore, and Maxime Descoteaux).

Brainlab sponsored an iPad for the winner.

Acknowledgments

Alexander Köhn, Christian Rieder, and Florian Weiler (Fraunhofer MEVIS) helped enormously with data preparation, the website, and documentation. Burckhard Terwey (Klinikum Bremen-Mitte) provided the data, and Nina Wehrmann (Centre Hospitalier Mayenne) helped select the patients. Neurosurgical experts Alexander Brawanski (Univ. Hospital Regensburg), Christopher Nimsky (Univ. Hospital of Marburg), Amir Samii (Int'l Neuroscience Inst. Hannover), Ulrich Sure (Univ. Hospital Essen/Duisburg), and Marcos Tatagiba (Univ. Hospital of Tübingen) evaluated the contest submissions. Russell Taylor (Univ. of North Carolina at Chapel Hill) has provided continued support for the contest.

can always switch back and forth between the steps to choose and analyze a new access path.

Step 1

Here, we combine 2D *slice views* enhanced with *lift charts* with a 3D *context view* integrating relevant information from the available modalities (see Figure 1a). The slice views provide insight into structures and let neurosurgeons identify structures in the tumor and diagnose its type. The context view depicts the tumor's location and relation to the structures at risk. We further overlay this view with a *tumor map* showing a projection of relevant structures as seen from the tumor.

To give a better view of the tumor and relevant adjacent structures, we provide a close-up tumor view (see Figure 1b). Here, surgeons can identify vessels and fibers that the tumor might infiltrate or displace. Using these views, they can place one or more access paths before analyzing and comparing them in step 2.

Step 2

To allow a comprehensive analysis of the chosen access path, we combine four displays.

First, the *probe view* shows all structures in the access path and provides a preview of how the path would look during the operation (see Figure 2a). It lets surgeons fine-tune the path.

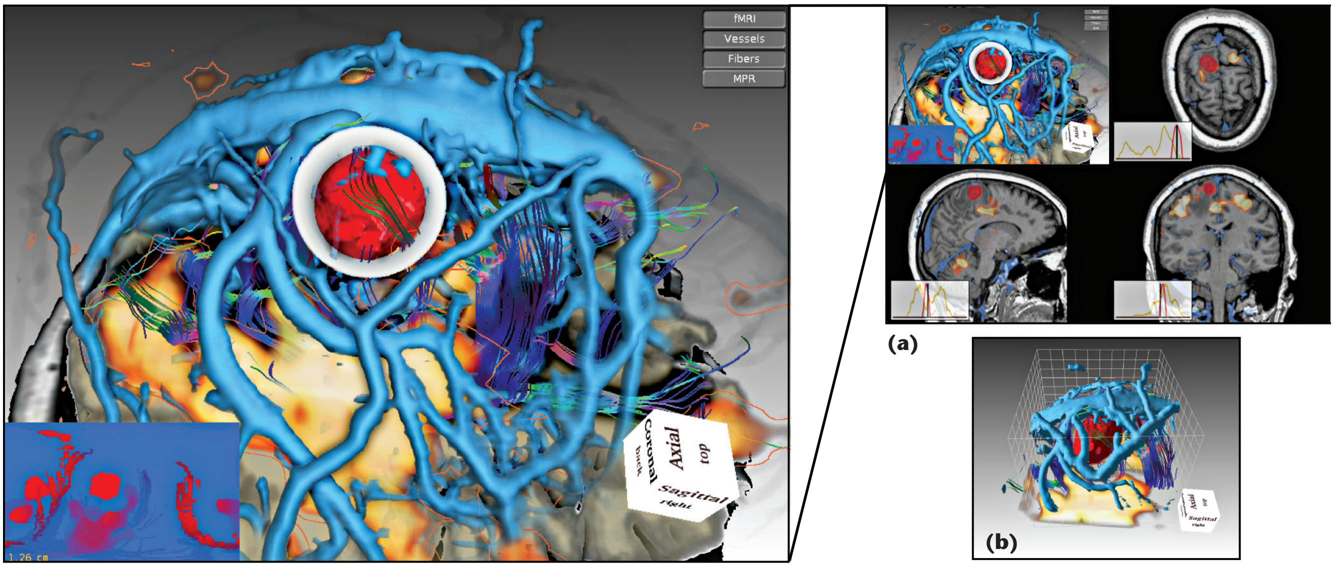

Figure 1. Workflow step 1. (a) By exploiting multimodal 2D and 3D views, neurosurgeons can explore the data and plan an initial access path. (b) The tumor view allows close-up inspection of the resection region.

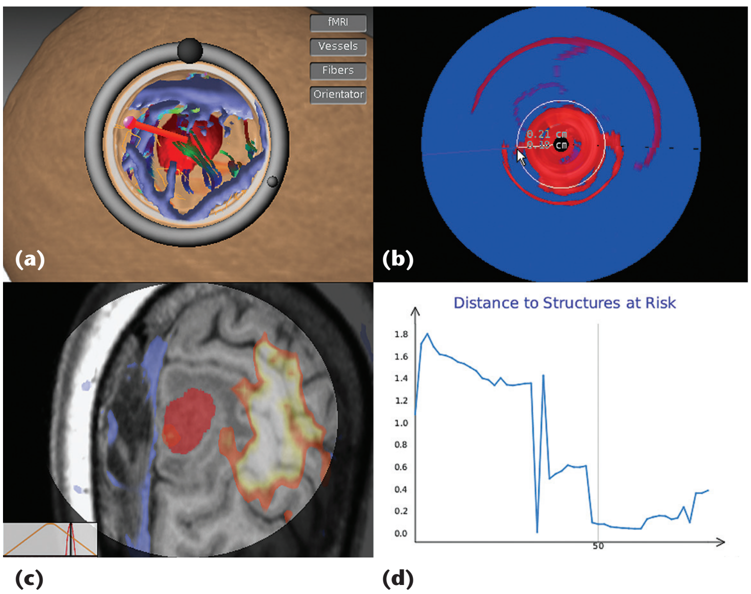

Figure 2. Workflow step 2. Neurosurgeons can inspect and modify the access path by exploiting (a) a probe view, (b) a cylindrical access-path projection, (c) a microscope slice view, and (d) an access-path distance plot.

Second, so that surgeons can locate structures near the access path, the *access-path projection* projects the structures surrounding the path onto the access-path cylinder's surface (see Figure 2b).

Third, the *slice view* centers on the access path and is oriented perpendicularly to it (see Figure 2c). This provides a view corresponding to the operation microscope focusing at a certain depth.

Finally, the *distance plot* shows the minimum distances of relevant structures along the access path, allowing easy comparison of possible paths (see Figure 2d).

Preprocessing

We segmented the vessels from the T1 dataset by using a random-walker-based segmentation system that Jörg-Stefan Praßni and his colleagues presented.[1] The contest datasets included brain and tumor masks, and the datasets were coregistered.

DTI Fiber Tracking

We used the Diffusion Toolkit[2] to perform fiber tracking before importing the resulting fiber lines into our application. Tracking can employ either the FACT (Fiber Assignment by Continuous Tracking) algorithm, a second-order Runge-Kutta method, interpolated streamlines (used for the images in this article), or tensorlines. To allow the extraction of relevant fiber tracts—for example, the pyramidal tract and the arcuate fasciculus—we support interactive region-of-interest definition. Furthermore, surgeons can filter the fibers on the basis of anisotropy, length, and direction.

DTI Uncertainty Extraction

To deal with the uncertainty introduced through DTI, we incorporate the fiber context and fiber anisotropy. Because DTI is less certain in regions near bone or air,[3] a volume analysis first applies a threshold to extract bone and air structures. On the basis of the thresholded volume, a distance transformation computes the distance to these structures for each fiber segment (see Figure 3). This will let surgeons define a security margin around bone and air structures. We normalize the computed distance to obtain a structural uncertainty U_S. To get the final uncertainty for a fiber segment, we combine U_S with the anisotropy uncertainty U_A to obtain the overall uncertainty, $U = \max(U_S, U_A)$.

Visualization

Here we discuss the visualizations the application prototype employs, focusing on our techniques for projection and uncertainty visualization.

2D and 3D Views

The 2D slice views are standard multimodal slice views. In the slice view, we overlay the shown modality with the tumor and the most important structures at risk—the areas with high fMRI activity and the vessels.

The enhanced lift charts were inspired by those that Christian Tietjen and his colleagues proposed.[4] For each slice, they depict the extent of malignant tissue (the red curve in Figure 4) and the fMRI signal (the yellow curve). We also indicate the current slice in the stack to help surgeons navigate through the slices.

Our system provides three different 3D views. The first is the context view. To prevent cluttering, surgeons can easily deactivate all modalities through onscreen buttons (see Figure 1a, top left). Additionally, they can activate a region of interest for the vessels on the basis of the distance to the tumor surface.

In the context view, surgeons can use the mouse to efficiently define the access path. When the surgeon clicks on the rendering, the system sets the intersection point with the skull (which can be transparent) as the access path's new starting point.

The second 3D view is the tumor view (see Figure 1b). Like the context view, it integrates all relevant modalities, but it displays a close-up showing only the tumor and structures in the tumor's proximity.

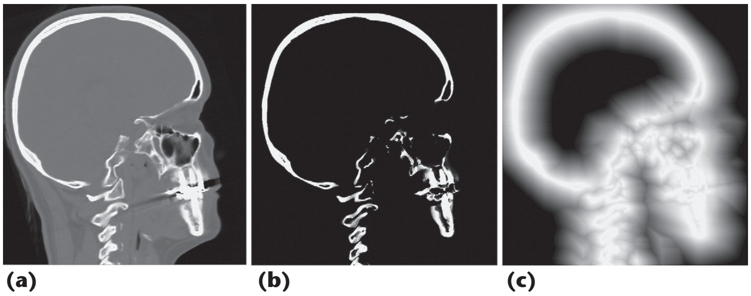

Figure 3. Extracting the diffusion tensor imaging (DTI) uncertainty. (a) A computed tomography (CT) scan. (b) The related bone mask. (c) The distance from the bones. The uncertainty is based on this distance, which is masked from the CT scan.

The third 3D view is the probe view. The orientation of the patient's head during the operation depends on the tumor's type and location. Surgeons can use the ring widget (see Figure 2a) to rotate the head around the fixed access-path axis to match the actual orientation. They can use the bigger ring marker as a rotation widget, with the smaller one pointing toward the patient's nose.

Projection

To provide surgeons with a quick overview of the most important structures at risk, we use two projection techniques: the tumor map and the access-path projection. Both employ an intuitive red-blue color mapping in which the nearby structures at risk are red.

To generate the distance images needed to calculate these views, we use a standard volume ray caster, parameterized by entry-exit-point (EEP) textures.[5] We pass spherical or cylindrical EEPs (see Figure 5a) to the ray caster and use the first hit points (see Figure 5b) to calculate the distance map (see Figure 5c). We ray trace the proxy geometry

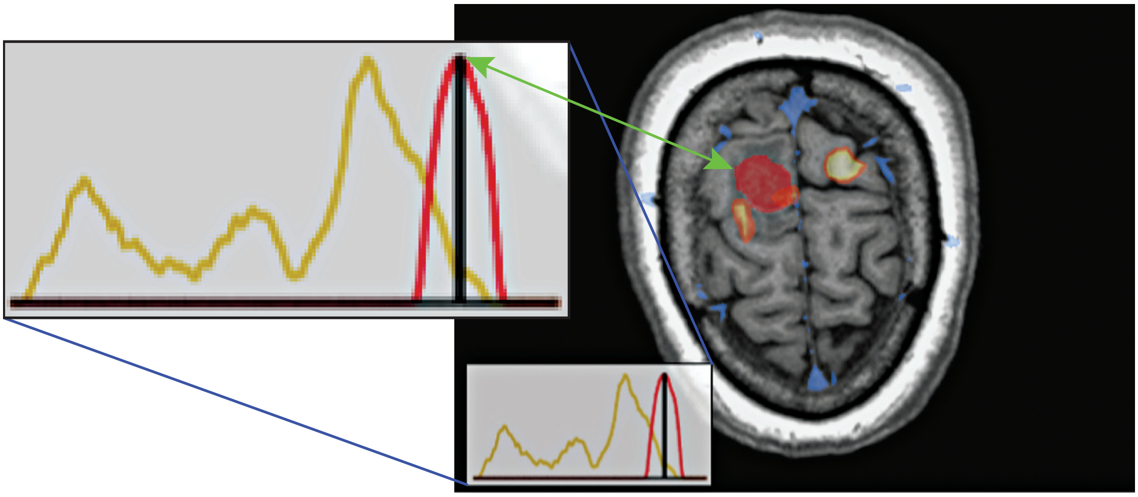

Figure 4. Enhanced lift charts indicate the current position in the slice stack and display the amount of malignant tissue (red) and the functional magnetic resonance imaging (fMRI) signal (yellow).

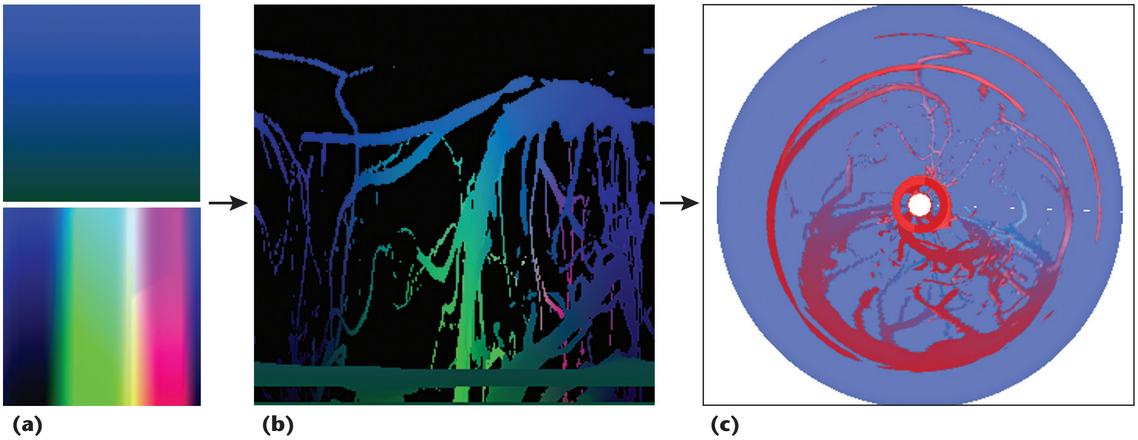

Figure 5. Calculation of projected views. (a) Cylindrical entry and exit points (color coded as proposed by Jens Krüger and Rüdiger Westermann[5]). (b) The result of the cylindrical ray casting (the first hit points, using the same color coding). (c) The resulting distances between the tumor/access path and the structures at risk, color coded and mapped to a disc.

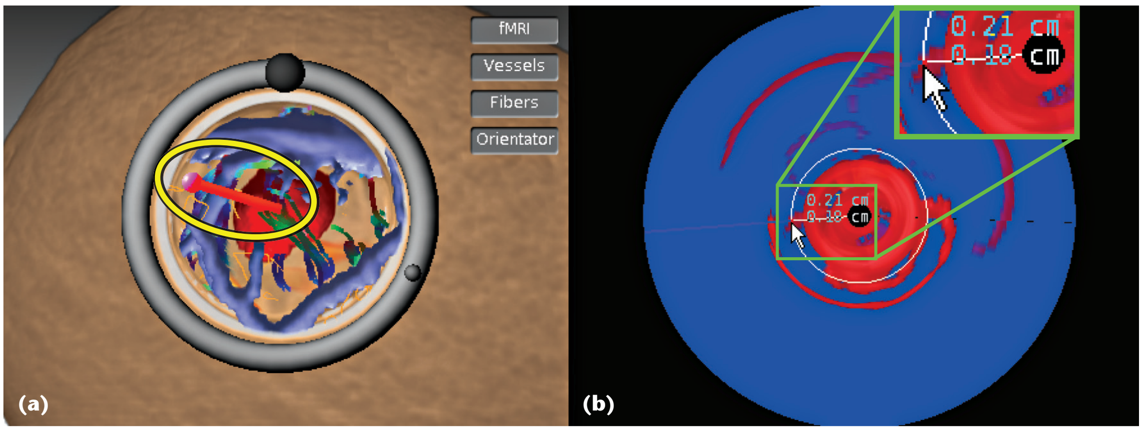

Figure 6. The probe view and access-path projection. (a) The probe view provides a preview of how the path would look during the operation. (b) This projection shows the distance to all relevant structures as seen from the access path. By moving the mouse over the distance map, users can quickly measure the depth along the access path and the distance to structures. The measured distance is also visualized in the probe view (the yellow circle).

with an OpenCL kernel to allow these types of projections.

The tumor map. This map was inspired by the projection type that Christian Rieder and his colleagues presented.[6] We calculate the distance to nearby structures at risk and color the results.

The tumor map has two uses. First, surgeons can quickly identify directions with few critical structures by looking for large blue areas. They can then directly set an access path in this direction by clicking on the map. Second, surgeons can move the mouse over the map to measure distances to structures, such as vital functional areas or the pyramidal tract. The system displays the distances in the context view.

We generate the map by performing two spherical ray castings from the tumor's center. First, we render the tumor mask using an inverted transfer function (that is, the tumor's interior is transparent, and the rest of it is opaque). We then use the first-hit points as entry points for a second ray casting of all the structures at risk. By calculating the distance between the entry and first-hit points for this ray casting, we get a distance map to which we apply the color mapping.

Access-path projection. Besides the distance from the structures at risk to the tumor, their distance to the access path is also important. So, the access-path projection shows the distance to all relevant structures as seen from the access path (see Figure 6b). We map this cylindrical projection's results to a disc, with the center of the projection representing the access path's deeper end. As with the tumor map, moving the cursor over a red region of the map automatically measures the distance to the structure at risk and displays it in the probe view

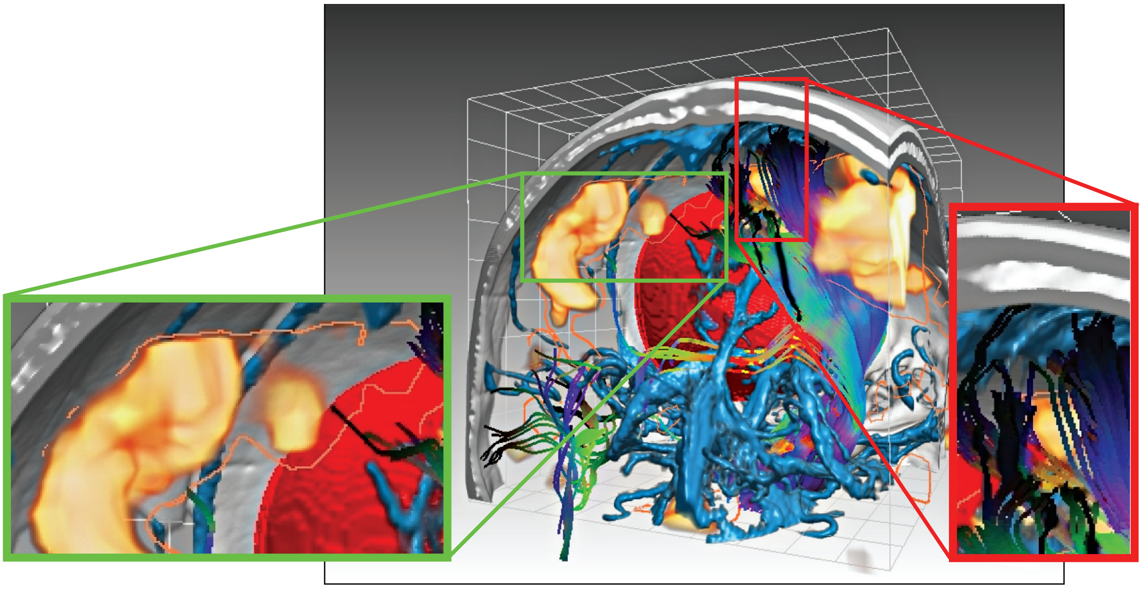

Figure 7. Uncertainty visualization. For fMRI (outlined in green), we render core regions using a diffusely emitting light signal; uncertainty borders are orange. For DTI (outlined in red), we render fibers close to bone and air with less saturation and brightness to mark them as uncertain.

(see Figure 6a). We also display the distance along the access path, which is important to surgeons.

Distance plots. To further facilitate assessment of the access path, we exploit an access-path cache together with the plot depicting the minimal distance to structures at risk along the path (see Figure 2c). Surgeons can use the cache like a bookmark, to cache paths of interest. By selecting different paths from the cache, surgeons can easily compare and modify them.

Uncertainty Visualization

Surgeons can visualize the uncertainty for both DTI and fMRI.

DTI. When visualizing the DTI fiber tracts, we incorporate the derived uncertainty information we introduced earlier. We encode the uncertainty in the saturation and value of the displayed fiber color in the HSV (hue, saturation, and value) color space. We determine the hue by the standardized directional fiber color-mapping that doctors are used to. We lower the saturation and value in regions of high uncertainty (see the area outlined in red in Figure 7). So, uncertain fibers become less emphasized, and their orientation, which can also be considered as less certain, is less prominent.

fMRI. Because of fMRI scans' low resolution and the possibility of partial highlighting of motor regions due to finger tapping, we render larger regions of uncertainty around core fMRI regions. We've applied an approach inspired by Tan Khoa Nguyen and his colleagues' research.[7] We display each fMRI region's core by exploiting a diffusely emitting light signal. Additionally, to express the uncertainty regarding these regions' size, we add an uncertainty margin, depicted by orange borders (see the area outlined in green in Figure 7). To generate this visualization, we render the fMRI signal twice. The first pass renders the core regions using a higher threshold; the second uses a lower threshold and applies an edge detection filter. We then composite this border image with the first pass's results.

Brain Rendering

Gradients in MRI scans are unreliable owing to noise. So, we use distance-based darkening (in which dark means deep) and depth darkening[8] to render the brain and simulate the effects of a global illumination model while minimizing the performance impact. We render the brain without shading (see Figure 8a) and apply depth darkening. The resulting image depicts the brain structures more comprehensibly (see Figures 8b and 8c). We then integrate the rendering into our multivolume ray casting by modifying the EEPs, as Hennig Scharsach proposed.[9]

Interaction Techniques

We've integrated several interaction techniques that support the mental linking of the different views and a deeper understanding of the data. Surgeons can intuitively measure distances between structures in the same modality or different modalities and specify or alter access paths,

Figure 8. Two techniques for shading the brain (using the same transfer function). (a) No shading. (b) Gradient-based shading. (c) Depth darkening, in which dark means deep. Depth darkening depicts the brain structures more comprehensibly.

as we mentioned before. Interactive navigation in all 3D views is possible at interactive frame rates, owing to GPU acceleration. The whole set of interaction techniques is demonstrated in a video, which is available at http://doi.ieeecomputersociety.org/10.1109/MCG.2011.70.

Evaluation

The two neurosurgeons who reviewed our entry in the contest rated our prototype's clinical value as high (7 and 9 out of 9). We've also demonstrated our application to our medical partners and received positive feedback. They liked that the enhanced lift charts provide a simple indication of the current position in the slice stack and indicate the amount of fMRI activity. They also felt that the 3D visualization intuitively integrates a wide range of modalities.

We would like to perform a more practical evaluation in which neurosurgeons actually use our application to plan access paths (instead of just watching a video). We would also like to investigate uncertainty visualizations for modalities other than DTI and fMRI. The current DTI uncertainty visualization can't be combined with shading techniques because users can't distinguish between low light and high uncertainty. We also need to integrate other sources of DTI uncertainty (for example, from the fiber-tracking algorithms).

For a brief overview of other related research on neurosurgical-planning software, see the following sidebar.

Acknowledgments

Grants from the Deutsche Forschungsgemeinschaft (German Research Foundation), SFB 656 MoBil Münster (project Z1), partly supported this research. The presented concepts have been integrated into the Voreen volume-rendering engine (www.voreen.org).

References

1. J.-S. Prassni, T. Ropinski, and K.H. Hinrichs, "Uncertainty-Aware Guided Volume Segmentation," *IEEE Trans. Computer Graphics and Visualization*, vol. 16, no. 6, pp. 1358–1365.
2. R. Wang et al., "Diffusion Toolkit: A Software Package for Diffusion Imaging Data Processing and Tractography," *Proc. Int'l Soc. Magnetic Resonance in Medicine*, vol. 15, 2007, p. 3720.
3. S. Cha, "Update on Brain Tumor Imaging," *Current Neurology and Neuroscience Reports*, vol. 5, no. 3, 2005, pp. 169–177.
4. C. Tietjen et al., "Enhancing Slice-Based Visualizations of Medical Volume Data," *Proc. Eurographics/IEEE VGTC Symp. Visualization* (EUROVIS 06), Eurographics Assoc., 2006, pp. 123–130.
5. J. Krüger and R. Westermann, "Acceleration Techniques for GPU-Based Volume Rendering," *Proc. 14th IEEE Visualization Conf.* (VIS 03), IEEE CS Press, 2003, pp. 287–292.
6. C. Rieder et al., "Visual Support for Interactive Post-interventional Assessment of Radiofrequency Ablation Therapy," *Computer Graphics Forum*, vol. 29, no. 3, 2010, pp. 1093–1102.
7. T.K. Nguyen et al., "Concurrent Volume Visualization of Real-Time fMRI," *Proc. Eurographics/IEEE VGTC Workshop Volume Graphics 2010*, Eurographics Assoc., 2010, pp. 53–60.
8. T. Luft, C. Colditz, and O. Deussen, "Image Enhancement by Unsharp Masking the Depth Buffer," *ACM Trans. Graphics*, vol. 25, no. 3, 2006, pp. 1206–1213.
9. H. Scharsach, "Advanced GPU Raycasting," *Proc. 2005 Central European Seminar Computer Graphics* (CESCG 05), 2005, pp. 67–76.

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Related Work in Neurosurgical-Planning Software

Neurosurgical-planning software has been an active research topic for several years. Here we focus on recent systems that use multivolume 3D visualization. Johanna Beyer and her colleagues developed an application that employs multivolume ray casting and skull peeling, a technique to selectively remove structures obscuring the brain without segmentation.[1] Christian Rieder and his colleagues devised a tool that uses distance-based transfer functions and visualizes the access path as a cylinder.[2]

Multivolume ray casting is an important part of neurosurgical-planning software. Examples of more recent implementations on modern GPUs are Stefan Lindholm and his colleagues' technique based on binary-space-partitioning trees[3] and Ralph Brecheisen and his colleagues' depth-peeling-based approach.[4] Bernhard Kainz and his colleagues proposed a renderer based on CUDA (Compute-Unified Device Architecture) that can handle multiple volumes combined with complex polyhedral objects.[5]

Visualization of DTI (diffusion tensor imaging) uncertainty was an important question in the 2010 IEEE Visualization contest (for more on this contest, see the other sidebar and the main article). However, to the best of our knowledge, Brecheisen and his colleagues have offered the only solution to visualize fiber-tracking uncertainty.[6]

References

1. J. Beyer et al., "High-Quality Multimodal Volume Rendering for Preoperative Planning of Neurosurgical Interventions," *IEEE Trans. Computer Graphics and Visualization*, vol. 13, no. 6, 2007, pp. 1696–1703.
2. C. Rieder et al., "Interactive Visualization of Multimodal Volume Data for Neurosurgical Tumor Treatment," *Computer Graphics Forum*, vol. 27, no. 3, 2008, pp. 1055–1062.
3. S. Lindholm et al., "Fused Multi-volume DVR Using Binary Space Partitioning," *Computer Graphics Forum*, vol. 28, no. 3, 2009, pp. 847–854.
4. R. Brecheisen et al., "Flexible GPU-Based Multi-volume Ray-Casting," *Proc. Vision, Modeling, and Visualization 2008*, 2008, pp. 303–312; www.mate.tue.nl/mate/pdfs/9881.pdf.
5. B. Kainz et al., "Ray Casting of Multiple Volumetric Datasets with Polyhedral Boundaries on Manycore GPUs," *Proc. ACM Siggraph Asia 2009 Papers*, ACM Press, 2009, article 152.
6. R. Brecheisen et al., "Parameter Sensitivity Visualization for DTI Fiber Tracking," *IEEE Trans. Computer Graphics and Visualization*, vol. 15, no. 6, 2009, pp. 1441–1448.

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