Eurographics Workshop on Visual Computing for Biology and Medicine (2010)
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Visualizing white matter fiber tracts with optimally fitted curved dissection surfaces

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Abstract

*Klingler dissection [LK56] as well as general blunt [Hei95] dissection of brain white matter shows the fiber bundles in the embedding tissue structures. White matter fiber tractography from diffusion tensor imaging (DTI) is, in general, visualized as 3D lines or tubes together with 2D anatomical MR slices or surfaces. However, determining the exact location of the fiber tracts in their surrounding anatomy is still unsolved. Rendering the embedding anatomy of fiber tracts provides new insight into the exact spatial arrangement of fiber bundles, their spatial relation, and tissue properties surrounding the tracts [SSA*08]. We propose a virtual Klingler dissection method of brain white matter creating curved dissection surfaces locally parallel to user specified fiber bundles. To achieve this effect in computer visualization, we create free-form clipping surfaces that align with the fiber structure of the brain and texture these according to structures they intersect or align with. An optimal view on the naturally embedding curved anatomical structure of the surrounding tissue enables the study of location and course of fiber bundles and the specific relation between different fiber systems in the brain. Indication of the local fiber orientation on the dissected brain surface leads to a representation of both, structural and directional information. The system is demonstrated on a human DTI dataset illustrating the dissection of the sub-insular white matter.*

Categories and Subject Descriptors (according to ACM CCS): Computer Graphics [I.3.3]: Line and Curve Generation—Life and Medical Sciences [J.3.1]: Health—

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1. Introduction

In contrast to conventional medical imaging, such as magnetic resonance imaging (MRI) or positron emission tomography (PET), diffusion-weighted MR imaging (dwMRI) yields complicated, multi-valued, information for each voxel. This information may comprise the vector of the main diffusion direction or even entire angular diffusion profiles. Moreover, in dwMRI the local information exhibits a great deal of global spatial coherence, which is of great importance for the interpretation. In particular, one may want to visualized fiber trajectories as well as entire fiber bundle systems. These specific properties of dwMRI pose substantial challenges to the classical way imaging data are visualized, which is based on planar cuts throught the volume (slices). One way to, partially, cope with this problem is to convey directional information using colors [CHPJ02], small vector representations or glyphes [Kin04]. These approaches share the common shortfall of only representing local information in the voxel, thus neglecting the global nature of the data. The other well established method is showing the fibers as streamlines [ZB02] or tubes [MEN*06]. While this excellently relays the global nature of the fibers, it fails at putting them into the appropriate anatomical context, as might be provided by conventional (T1 or T2) MR images. Usually, such fiber representations are displayed together with one more or less arbitrarily chosen MR slice. However the precise spatial location of the fibers in their surrounding tissue is of great interest in Neurosurgery, and cognitive Neu-

DOI: 10.2312/VCBM/VCBM10/041-048

roscience. In planning neurosurgical interventions it is important not to damage important white matter fiber bundles. Only in vivo visualization can be used to identify the individual location of these bundles. In Neuroscience the identification of functional networks needs an exact correspondence between functional activations (as reveled by fMRI) and the fiber bundles connect these areas. The detailed knowledge of the involved fiber system in a particular cognitive task is crucial for the analysis and interpretation of brain function.. This challenges visualization to come up with novel ways of imaging. For the first time, the problem was tackled by Schultz et al. [SSA*08]. Instead of planar slices, they used deformed surfaces to map the contextual MRI. These surfaces were chosen such that they match as closely as possible the mean trajectories of the fiber bundle. Both, curved MRI surfaces and fiber bundles are then displayed concurrently. This provides much more precise information on the brain structures a fiber tract passes or touches. However, this method only allows for displaying a small number of fiber tracts, since otherwise the anatomical background information would be obscured. As a matter of fact, it is often of great interest to assess larger systems of fiber bundles within the anatomy they are embedded in. This can be elegantly achieved by using a novel procedure, we are going to describe in this paper. For this, we utilize so-called LIC (line integral convolution) textures [CL93], which allow to map the principal fiber direction directly onto the curved MRI slices. Similar methods have been used in vector field visualization and our method was inspired by the approaches of Laramee et al. [LJH03] and the ideas of Hotz et al. [HFH*06], who used texture on surfaces to analyze engineering tensor data. This way one can achieve global views of entire white matter fiber systems, embedded into the anatomical context. Similar effects have been already created for many decades by various dissection methods applied to *post mortem* brains, such as blunt dissection [Hei95] or Klingler dissection [LK56] (cf. Fig. 1). However, in contrast to these techniques, which only work with cadaver brains and require a great amount of tedious work by highly skilled experts, our method works automatically on images of the living brain.

The remainder of this paper is organized as follows. We provide details on the surface calculation (Section 2) and describe the method for texture generation (Section 3). Finally, we present details of the implementation (Section 4) and discuss the results and potential future research (Section 5).

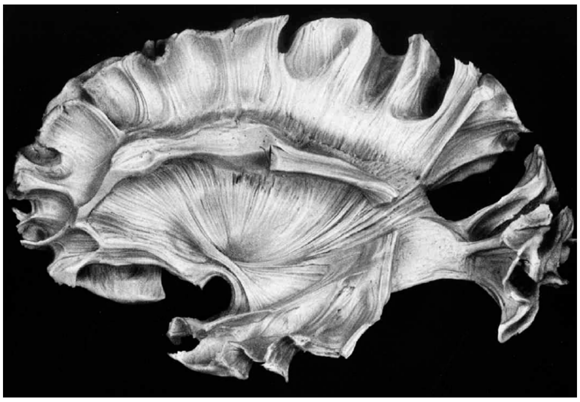

Figure 1: *Our work was motivated by photographs of dissected human brains. Neuroanatomists cut away tissue until they reach areas of the brain they want to see. These usually follow the fibrous structure of the neural nerves (Picture taken from [LK56])*

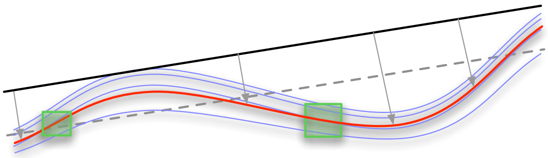

Figure 2: *Illustration of surface generation: The initial plane (back) is positioned by the user to align with the fiber structure (blue), leading to a surface (red) aligning with the fiber structure. In this simple example, a principal component analysis would generate the gray, dashed line and lead to the same results (see text). A selection of fibers can be provided by, for example, Boolean operations applied to fibers intersecting different boxes, indicated by green rectangles here.*

2. Surface Calculation

When performing a Klingler dissection on a post-mortem brain, the first step is to cut through the brain along an imaginary plane until the structures of interest are reached. In our virtual dissection environment, this plane is initially given by the user as an arbitrary sweeping plane that is chosen in a way such that it provides the required contextual information (Fig. 2). The information provided by the user usually is limited to the orientation of the clipping plane and its offset to the important structures, i.e., the selected fiber bundles.

Having both the structural information and the contextual information, the next step is the deformation of the plane to obtain an optimal cut along the structural information.

We start with a spline representation of the surface. The surface is then bent using points on the selected lines as scattered data that is interpolated using Shepard interpolation with Franke-Little weights (for example, as reported in [Bar77]). Therefore, the value $v(p)$ is

$$v(p) = \frac{\sum_i \xi_i^\mu v(p_i)}{\sum_i \xi_i^\mu}, \qquad (1)$$

with

$$d(p_1, p_2) = \|p_1 - p_2\| \tag{2}$$

and

$$\xi_i = \begin{cases} 1 - d(p, p_i)/r & d(p, p_i) < r \\ 0 & otherwise, \end{cases} \tag{3}$$

where μ is a weight factor and r is the radius of the interpolation kernel. We use $\mu = 8$ and $r = 30$ *mm*. Even though this would lead to a smooth representation of the surface, we have choose a spline representation for several reasons:

- The final representation uses fewer points and is therefore easier to store,
- efficient techniques for rendering exist, and
- it allows for editing the surface by the user afterwards.

In other words, we place a grid of an arbitrary, adjustable number of de Boor control points on the initial sweeping plane. For every control point the center of mass of the nearby fibers is calculated and the control point is moved to that center. If the number of fibers within the range of the control point is lower than a given minimum, that point is discarded. We keep some control points at the edges of the plane to maintain the overall alignment. This procedure creates a deformed surface that follows the selected fiber bundles. In case this automatic process does not produce an optimal result, the user can still manually manipulate the control points and even add more.

3. Texture Generation

Instead of displaying geometrical information only, medical textbooks highlight the texture as well. This is mandatory for distinction of different types of tissue, especially their directional alignment. Therefore, we decided to adapt this type of visualization to our virtual dissection by displaying the fiber structure of neural tissue similar to, for example, Gray's Anatomy [Gra18].

The texture generation consists of two steps: a tensor LIC and a color coding of the directional information. We first want to explain the line integral convolution technique.

The basic idea of line integral convolution arose from experiments using oil on surfaces that build “Schlieren” along the main directions of the air flow. This method has been adapted and is now used as a general means to describe directional information along surfaces. While a similar method was used by Hotz et al. [HFH*06] for tensor data from engineering applications, we use a simplified method as only one main direction is indicated in the final image.

First, tensor information is mapped to the surface generating one tensor per cell. The major eigenvector is then mapped into the surface leading to one orientation vector per triangular surface cell. Then, an initial texture is created using salt-and-pepper noise on the surface leading to a binary texture. Anisotropic smoothing is applied based on this information and a moving kernel, locally scaled by the in-surface amount of the eigenvector to maintain reasonable results when the eigenvectors are perpendicular to the plane.

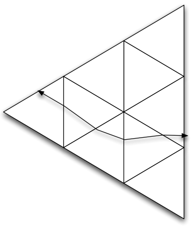

Figure 3: *The geometry-based approach on a triangular grid: Lines are integrated using piecewise-constant interpolation in triangle cells, which makes the line integration efficient. Errors are neglectable due to the limited integration length (implied by the kernel size) and the high resolution of the grid. Note, that the eigenvectors only provide tangential information; the orientation of the eigenvector is not important. An additional scaling of the parameterization can be introduced using local fractional anisotropy.*

Due to the high resolution of the grid, constant interpolation inside a cell is sufficient to achieve reasonable results (cf. Fig. 3). We randomly seed lines in the data set and mark the number of lines intersecting each triangle. The triangles that are not touched by a minimum number of lines (for example, at least two lines) are used as additional seeds for new lines until the whole surface is densely covered by lines.

When compared to methods using parameterized textures, where the triangulation is determined by the curvature of the surface, our approach requires a larger amount of triangles (i.e., the triangle resolution has to be similar to the display resolution). However, no global parameterization is required, which makes the approach applicable to any smooth surface of arbitrary topology.

3.1. Improvements

While the above approach already leads to good results in areas where the fiber orientations are parallel to the clipping plane, i.e. close to the previously selected fiber bundles, it could return misleading results where there is low FA or the fibers are almost perpendicular to the surface. To counter that we implemented two adjustments. In areas with low FA we think there is no dominant fiber direction so we rather show no texture at all. The FA is here used as a blend factor, which means the LIC texture disappears seamlessly the lower the FA gets. For areas where there is high enough FA but the major eigenvector is perpendicular to the plane we leave the noise texture unchanged to give the impression of looking onto cut fibers (see Fig. 4).

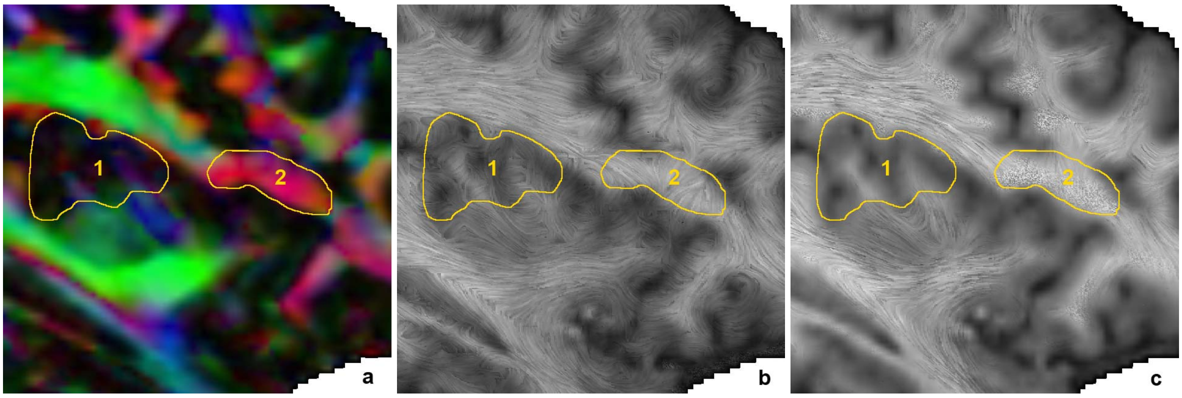

Figure 4: *Three different views of a selected sub section on a sagittal slice of a human brain. The marked areas represent voxels with low FA (1) or voxels in which the major eigen vector is perpendicular to the plane (2). Figure b shows how a LIC algorithm without adjustments would respond to these problems. As it can be seen, the LIC shows directional information, that is either not there (1) or is entirely different (2). Figure c shows how our algorithm blends off the LIC texture (1) or leaves the noise texture unchangend (2)*

3.2. Color Coding

Depending on the application, different color coding schemes are suitable:

Structural Color Coding: In this approach, the color coding is set according to the structural information gained from additional MRI scans, such as T1 or T2 images. We modulate the texture using this information to indicate the white matter–gray matter boundary.

Directional Information: Another approach uses the color coding depending on the tensor information, such as tensor direction and fractional anisotropy (FA). Here, we modulate the color information using the standard medical RGB color scheme with the texture. This intensifies the fiber direction especially in areas where the line structure is perpendicular to the plane of interest.

Structural and Directional Information: By combining the previous pictures, i.e., modulating the directional color coding using anatomical T1 information, we highlight anatomical information on top of the directional information. This eases navigation as, in addition to the directional color scheme, which is the default in neuroscience and neurosurgery, it provides anatomical information. The blending can be changed interactively.

Alternative Color Codings: Whereas the basic idea of our approach is to put structural and directional information in context, it turns out that for most approaches, a gray-scale encoding of the texture is sufficient. As the texture mainly contains high-frequency components, almost the entire color space remains available to augment the surface with additional information, for example, functional data. This seems to be a reasonable approach because analysis of functional imaging, i.e., analysis of active areas of the brain, goes along with understanding of brain connectivity which is shown in our method. We have not yet performed in-depth user studies concerning this multi-modal visualization approach, and plan to address this aspect in future research.

4. Implementation

We implemented the approaches in a tool using the platform-independent libraries wxWidgets and OpenGL libraries for the graphical user interface. During the implementation we focused on standard hardware, and therefore, the system can be deployed in most research and clinical environments without additional costs. Nevertheless, the system tries to utilize the available resources, for example, it uses parallelization on shared memory systems and supports hardware-accelerated rendering.

The timings were generated based on a standard Linux PC, Intel Core 2 Quad CPU at 2.3 GHz, 4 GB RAM, and a GeForce 8800 GTX graphics board.

kd-Tree and Fiber Selection: We implemented a parallel implementation of the kd-Tree that can be constructed in less than one second for 74 313 lines with a total of approximately 5.6 million points (ca. 120MB), and in six seconds for 400 000 lines and approximately 29 million points (ca. 600MB). Queries can be performed at interactive speeds where we allow Boolean relationships between boxes to be able to select the fibers of interest (AND, OR, and NOT operatiors are currently implemented.) For the graphical representation, the user can choose between unshaded lines, shaded lines [ZSH96], and a tube representation similar to [SBK06, MEN*06] that allow interactivity while providing high visual quality.

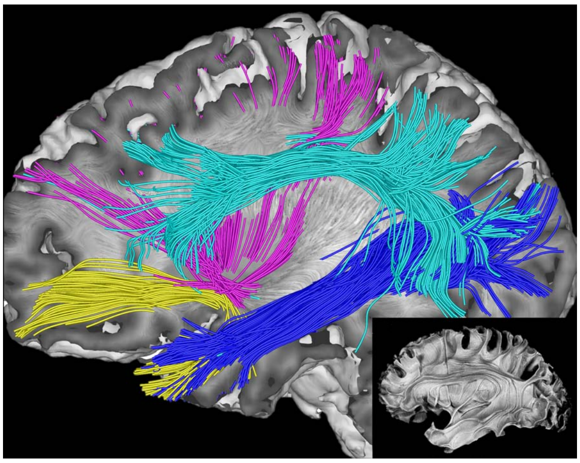

Figure 5: *Example of a virtual Klingler dissection of the fronto-temporal fiber system. The superior longitudinal fasciculus SLF (turquoise), the uncinate fasciculus UNC (yellow), the inferior longitudinal fasciculus ILF (blue) and the external/extreme capsule EC/EMC (violet) are overlaid on the dissection surface. The inset shows a corresponding post mortem Klingler dissection ([LK56]).*

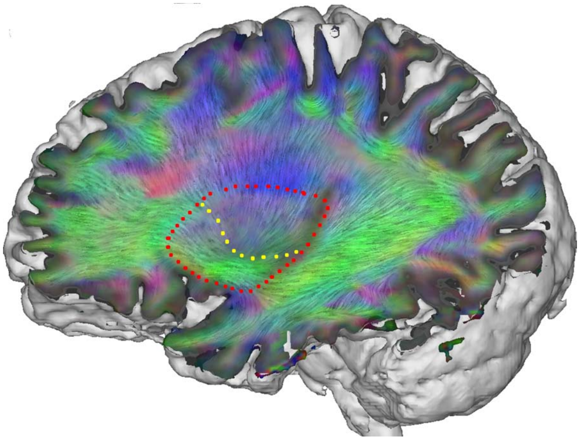

Figure 6: *Dissection of the sub-insular white matter: color-coded diffusion texture shows fine anatomical details of the local tissue orientation in the white matter underneath the insular cortex (outlined in red). The texture indicates structural connections of the posterior-dorsal part to the somatomotor areas and of the inferio-frontal fraction to frontal and temporal areas. The yellow line indicates the suggested rostrocaudal separation of the sub-insular white matter..*

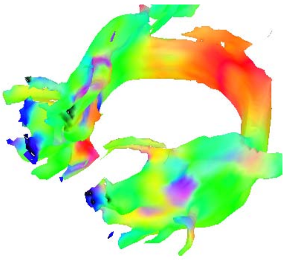

Figure 7: *Directional color coding on a probabilistic fiber tracking in the human brain.*

5. Results

5.1. Virtual dissection of a complex fiber system

The method was applied to study the fronto-temporal fiber system and the sub-insular white matter system. The fronto-temporal fiber system is dominated by the superior longitudinal fasciculus (SLF), the inferior longitudinal fasciculus (ILF) end the external/extreme capsule fiber system (EC/EMC). These bundles were interactively identified and selected as starting fiber to fit the dissecting spline surface. While interpolating between the selected bundles and smoothly extrapolating to the surface of the brain, the dissection surface showed the white matter structure naturally embedding the fiber bundles which allows an exact localization of the 3D course and the anatomical endings of the fiber bundles (Figure 5). Texturing the surface with the LIC texture combined with the gray value of the T1 anatomy allows studying the extension of the white matter structure in the vicinity of the bundles. The texturing indicates a continuity of the white matter structure which is parallel to the selected fiber structures, but which extend the classically defined bundles in a smooth way between the bundles and to the cortex. The result closely matches an example of a post-mortem Klingler dissection of a similar fiber structure (Inset in Figure 5).

5.2. Enhanced visualization of white matter sheets

A second application shows the dissection of the sub-insular white matter which is dominated by the fibers of the extreme/external capsule. A curved surface was fitted to this fiber system and textured with the diffusion orientation and the color-coding of the main diffusion directions (Figure 6). The corresponding post mortem Klingler dissection is shown in Figure 1. The color-coded diffusion texture shows fine anatomical details of the local tissue orientation in the white matter underneath the insular cortex (outlined in red). The texture indicates structural connections of the posterior-dorsal part to the somatomotor areas and of the inferio-frontal fraction to frontal and temporal areas. The yellow line indicates the suggested rostrocaudal separation of the sub-insular white matter.

5.3. Application to Probabilistic Tracking

As our approach can be applied to surfaces with arbitrary topology, any isosurface can be textured. Instead of using

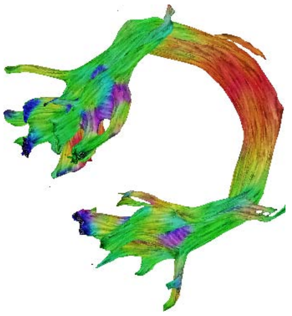

Figure 8: *Directional color coding with texturing on a probabilistic fiber tracking in the human brain.*

deterministic fiber tracking as discussed before, probabilistic approaches estimate the connectivity between different areas of the brain, leading to a scalar field known as *connectivity map* [ATvC*07]. It describes a unit-free amount of connectivity between a chosen seed voxel or area to any other voxel in the data set. In general, isosurfaces and volume rendering are used to delineate highly connected regions but usually neither of these indicates directional information. Only geometrical information is displayed, which can be compared to the enveloping surface of the selected fiber structure. While a color coding (see Fig. 7) provides directional hints, its interpretation is not obvious. We texture these surfaces depending on the local structure as shown in Fig. 8: Here, directional structure becomes visible without providing additional details of the white matter structure.

6. Discussion

We have shown that using a global visualization method like the LIC improves the holistic perception of inherently local (voxel bases) data. With previous approaches, like color coding or vector plots, it requires a great deal of experience and three-dimensional imagination to achieve a similar effect. On the other hand, rendering fibers as streamlines or tubes is a great solution for presenting small fiber selections, but gets confusing for complex fiber systems, in particular if one wants to convey the precise anatomical context of the fibers at the same time. Our approach aims at combining both worlds. Unlike the dissection approach by Schultz et al. [SSA*08], who carve out the surrounding tissue from the contextual MRI slice and display fibers as streamlines on to of this, with the above mentioned disadvantages, we show the information directly on the dissection surface.

However, one might criticise that using a LIC texture for dwMRI data gives a false impression of direction in areas where the major eigenvector is not parallel to the surface in question or where there is no dominant fiber direction. This problem was identified to originate from the projection of the major eigenvector onto the surface. One thinkable approach would be to stop the streamline integration (for the convolution filter) when the length of the projected vector goes below a certain value. However our testing of this idea led to unsatisfying results. Our new approach tackles these problems from a different perspective. By deforming the cutting plane to follow the shape of the fiber bundles, which are derived from the same dwMRI data, we make sure that the direction information is indeed correct, at least for those portions of the dissection surface that are close to the fiber bundle. This only leaves areas where there is an arbitrary alignment of the surface to the fiber structure. Although these areas are implicitly of lower interest, our adjustments assure that only correct directional information is displayed. The quality of the local matching of the smooth spline surface to the fiber bundle depends on the locale curvature of the bundle. In general the spline surface matches quite well in the central parts of the bundle. Fiber endings often correspond to strong curvature and also a strong spreading of the bundle. Therefore a matching of a single surface is more difficult, and the accuracy is reduced. Manual adaptation of the spline surface can visualize the important features.

7. Conclusion and Future Work

We have presented a way of mapping directional data to a non planar surface in the brain which is adapted to the shape of major fiber bundle systems. While the ingredients of our method are not new in themselves, e.g. LIC is used in flow visualization for decades, their application on non planar dissection surfaces for dwMRI is unique and provides additional and better insight into structures otherwise hidden. Displaying the directional information directly on the surface provides two main advantages. First there is no need to display fibers (as streamlines or tubes) which may complecate the picture and obstruct the view onto essential anatomical details. Second, since the LIC texture provides the directional information the color value of the voxel is still "free" and can be used to relay any other information (e.g. functional activity or FA). The procedure is implemented to work almost completely automatic after a few initial manual settings and provides satisfiable results even for users with minimal training. Our further research will be directed at integrating recent methods such as presented by Schultz et al. [SS08] that have proven to be capable of deriving multiple fiber directions from a data set.

8. Acknowledgements

Part of this work is supported by the FET project CONNECT of the European Union: http://neuroimaging.tau.ac.il/CONNECT

We would like to thank our collaborators for giving useful hints on the usability and design of the software tool. Special thanks go to Tobias Göbel (MD cand.) for his comments on the user interface design.

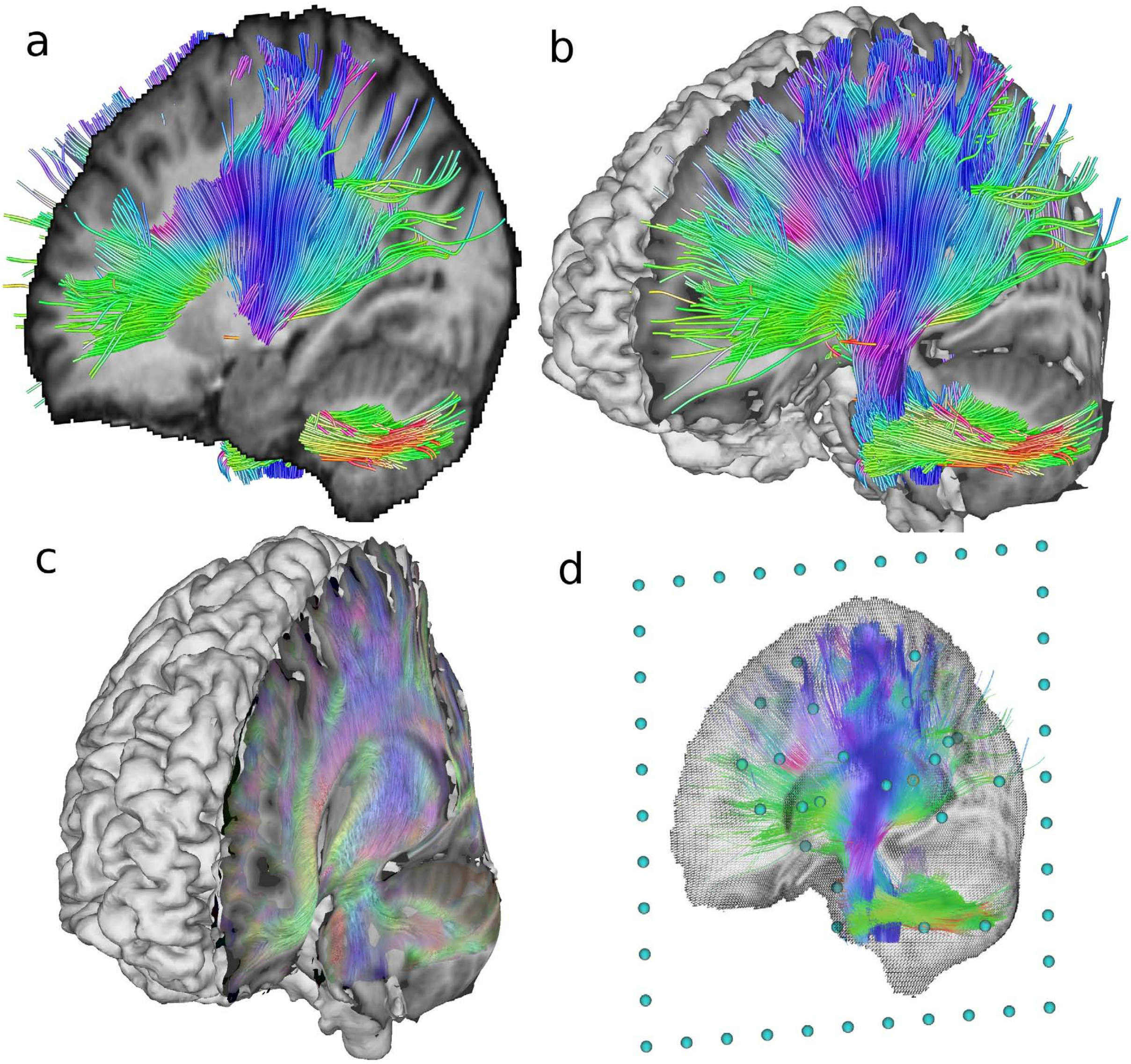

Figure 9: *Virtual Klingler dissection: a specific fiber bundle and an initial anatomical slice is selected (a); a spline surface is matched to fibers (b); the curved dissection plane is textured with the fiber orientation (c); control points of the spline surface for interactive optimization of the final shape (d)..*

References

[ATvC*07] ANWANDER A., TITTGEMEYER M., VON CRAMON D., FRIEDERICI A., KNÖSCHE T. R.: Connectivity-based parcellation of broca's area. *Cerebral Cortex 17*, 4 (2007), 816–825.

[Bar77] BARNHILL R.: Representation and approximation of surfaces. *Mathematical Software III* (1977), 69–120.

[CHPJ02] CATANI M., HOWARD R. J., PAJEVIC S., JONES D. K.: Virtual in vivo interactive dissection of white matter fasciculi in the human brain. *NeuroImage 17* (2002), 77–94.

[CL93] CABRAL B., LEEDOM L. C.: Imaging Vector Fields Using Line Integral Convolution. In *SIGGRAPH '93: Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques* (New York, NY, USA, 1993), ACM Press, pp. 263–270.

[Gra18] GRAY H.: *Anatomy of the Human Body, by Henry Gray*, 20 ed. Philadelphia: Lea and Febiger, 1918.

[Hei95] HEIMER L.: *The Human Brain and Spinal Cord: Functional Neuroanatomy and Dissection Guide*. Springer Verlag, 1995.

[HFH*06] HOTZ I., FENG L., HAGEN H., HAMANN B., JOY K. I.: Tensor field visualization using a metric interpretation. In *Visualization and Processing of Tensor Fields* (2006), Weickert J., Hagen H., (Eds.), Springer–Verlag Berlin Heidelberg, pp. 269–281.

[Kin04] KINDLMANN G.: Superquadric tensor glyph. *Joint EUROGRAPHICS – IEEE TCVG Symposium on Visualization* (2004).

[LJH03] LARAMEE R. S., JOBARD B., HAUSER H.: Image space based visualization of unsteady flow on surfaces. *Proceedings of IEEE Visualization 2003* (2003).

[LK56] LUDWIG E., KLINGLER J.: *Atlas cerebri humani: the inner structure of the brain demonstrated on the basis of macroscopical preparations.* Boston : Little, Brown, c1956., 1956.

[MEN*06] MERHOF D., ENDERS M. S. F., NIMSKY C., HASTREITER P., GREINER G.: Hybrid visualization for white matter tracts using triangle strips and point sprites. *IEEE Transactions on Visualization and Computer Graphics 12* (Oct. 2006), 1181–1188.

[SBK06] SCHIRSKI M., BISCHOF C., KUHLEN T.: Interactive Particle Tracing on Tetrahedral Grids Using the GPU. In *Proceedings of Vision, Modeling, and Visualization (VMV) 2006* (2006), pp. 153–160.

[SS08] SCHULTZ T., SEIDEL H.-P.: Estimating crossing fibers: A tensor decomposition approach. *IEEE Transactions on Visualization and Computer Graphics (Proc. IEEE Visualization) 14*, 6 (2008), 1635–1642.

[SSA*08] SCHULTZ T., SAUBER N., ANWANDER A., THEISEL H., SEIDEL H.-P.: Virtual klingler dissection: Putting fibers into context. *Computer Graphics Forum 27*, 3 (2008), 1063–1070.

[ZB02] ZHUKOV L., BARR A. H.: Oriented tensor reconstruction: Tracing neural pathways from diffusion tensor MRI. In *Proceedings of IEEE Visualization '02* (Los Alamitos, CA, 2002), IEEE Computer Society, pp. 387–394.

[ZSH96] ZÖCKLER M., STALLING D., HEGE H.-C.: Interactive visualization of 3D-vector fields using illuminated stream lines. *IEEE Visualization* (1996), 107–113,474.