Advanced Texturing Techniques for the Effective Visualization of Neuroanatomy from Diffusion Tensor Imaging Data

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Abstract

Diffusion Tensor Imaging (DTI) is a relatively new imaging modality which can be used to gain in vivo information about the anatomy of the brain. This paper presents three new techniques for the visualization of DTI slice data: Barycentric colour maps allow an integrated view of different types of diffusion anisotropy. Ellipsoid-based textures and Anisotropy Modulated Line Integral Convolution create images which are segmented by tissue type and incorporate a texture representing the 3D orientation of nerve fibers. The effectiveness of the new visualization techniques is demonstrated by identifying various anatomical structures and properties from a diffusion tensor data set of a healthy brain.

Keywords: Biomedical Visualization, Diffusion Tensor Imaging, Texturing, Brain Anatomy, Nerve Fiber Tracking.

1 Introduction

A common problem in biomedical sciences is the in vivo identification and analysis of anatomical structures. This paper introduces several novel techniques to visualize tissue types, nerve fiber tracts, and differences in the structure of nerve fiber tracts in the brain using diffusion-weighted MRI slice data.

The diffusion tensor describes the spatial distribution of water molecules originating at a common location. Since the diffusion of water depends on the micro-structure of the tissue, the diffusion tensor field can be used to visualize nerve fibers and other tissues in the brain. The resulting images of the brain anatomy can be used to advance research in surgical planning, cognitive sciences, and the diagnosis and treatment of various white and gray matter disorders (Pierpaoli, Jezzard, Basser, Barnett & Chiro 1996, Lim, Hedehus, Moseley, de Crespigny, Sullivan & Pfefferbaum 1999, Barnea-Goraly, Eliez, Hedeus, Menon, White, Moseley & Reiss 2003). Visualizing the nerve fiber structure also represents a valuable teaching tool.

The next section introduces diffusion tensor imaging and describes how it can be used to differentiate tissue types. A summary of derived measures is followed by a short review of previous work in this domain. The main body of this work presents several novel techniques for visualizing DTI slice images. Our approach starts with colour mapped slice images familiar to the medical specialist and progressively expands the complexity and amount of information encoded in the images. The quality of our visualization techniques is demonstrated by identifying various anatomical structures and features in a diffusion tensor data set of a healthy brain.

2 Diffusion Tensor Imaging

Diffusion tensor imaging (DTI), also known as *diffusion-weighted MRI imaging* (DWI), is used to measure the intrinsic properties of water diffusion in the brain by an orientation invariant quantity, the diffusion tensor **D** (Basser, Mattiello & Bihan 1994, Basser 1995). The eigenvalues and eigenvectors of the symmetric second-order tensor **D** define the principal axes of a *diffusion ellipsoid* which expresses the spatial distribution of water molecules originating at a point location after an infinitesimal time period.

DTI almost completely suppresses water in the blood vessels (Basser 2000) and can be used to measure the diffusion of cerebral spinal fluid (CSF) and fluid inside of nerve cells. The results of the measurement are the six components of the symmetric diffusion tensor **D** and the T_2 weighted signal intensity in the absence of diffusion sensitization. Images of water diffusion can provide pathophysiological information complementary to T_1 and T_2 weighted MRI images. The technique is sensitive to movements of the order of a few microns and is described in more detail in (Basser & Pierpaoli 1996, Pierpaoli et al. 1996, Aronen, Korvenoja, Martinkauppi, Perkiö, Karonen & Carlson 1999).

In the brain DTI can be used to differentiate three types of structures. Fluid filled compartments are characterized by a very high *isotropic* diffusion, i.e., the diffusion is similar in all directions. In contrast nerve fibers restrict the diffusion to one direction only due to the presence of cell membranes and myelin sheaths surrounding the axons. Fiber tracts, consisting of millions of parallel nerve fibers, are therefore identified as areas of a high *anisotropic* diffusion. The orientation of such fiber tracts is determined from the principal directions of the diffusion tensor. Finally gray matter is characterized by a low and nearly isotropic diffusion since the water diffusion is restricted in all directions due to cell membranes of intermingled cell bodies and their surrounding neuraglia. Consequently DTI can be used to gain in vivo information about the anatomy, microstructure and physiology of the brain.

DTI imaging has been successfully applied to diagnose various diseases. For schizophrenic patients it has been found that the fractional anisotropy in the frontal lobes is reduced despite having no significant volume deficit (Lim et al. 1999). Assaf et al. report that DTI images are also sensitive to the

pathophysiological state of white matter in brains diagnosed with Multiple Sclerosis (Assaf, Ben-Bashat, Chapman, Peled, Biton, Kafri, Segev, Hendler, Korczyn, Graif & Cohen 2002). Barnea-Goraly et al. show that regionally specific alterations of white matter integrity occur in patients with *Fragile X Syndrom*, a common form of hereditary mental retardation (Barnea-Goraly et al. 2003).

2.1 Derived Quantities

The matrix representation of a second-order tensor depends on the coordinate system used (MRI coordinates). In order to describe intrinsic tissue properties variables independent on the patient's position must be derived. Examples are the three tensor invariants. An important property of any 3-dimensional symmetric second-order tensor $\mathbf{T}$ is that there always exist 3 *eigenvalues* λ_i and 3 mutually perpendicular *eigenvectors* $\mathbf{v}_i$ such that

$$\mathbf{T}\mathbf{v}_i = \lambda_i \mathbf{v}_i \quad i = 1, \ldots, 3 \tag{1}$$

As mentioned previously the eigenvalues and eigenvectors of the diffusion tensor $\mathbf{D}$ define the principal axes of a diffusion ellipsoid. To facilitate the definition of new measures it is convenient to order the three eigenvalues of the diffusion tensor $\mathbf{D}$ by size with λ_1 being the biggest and λ_3 being the smallest (Pierpaoli et al. 1996). The *maximum diffusivity* is then given by $\lambda_{max} = \lambda_1$.

The *mean diffusivity* is defined as the average eigenvalue of the diffusion tensor and is efficiently computed by using the first tensor invariant

$$\lambda_{mean} = \frac{\lambda_1+\lambda_2+\lambda_3}{3} = \frac{trace(\mathbf{D})}{3} = \frac{D_{11}+D_{22}+D_{33}}{3} \tag{2}$$

Images of λ_{mean} show all brain tissue and fluid filled compartments. Note that the computation does not require the computation of the eigenvalues but involves merely averaging the diagonal elements of the tensor matrix.

Another important measure is the anisotropy of the diffusion tensor. We define it as

$$\begin{aligned} \lambda_{aniso} &= trace((\mathbf{D} - \lambda_{mean}\mathbf{I})^2)/\lambda_{mean}^2 \\ &= ((\mathbf{D} - \lambda_{mean}\mathbf{I})^T(\mathbf{D} - \lambda_{mean}\mathbf{I}))/\lambda_{mean}^2 \end{aligned} \tag{3}$$

which was suggested to us by Peter Basser (Basser 2000). Note that the computation is efficient and does not require the computation of the eigenvalues. The measure is used to identify regions where $\lambda_1 >> \lambda_2 \geq \lambda_3$ and can be used to detect nerve fiber tracts.

Additional measures have been proposed by Westin et al. (Westin, Peled, Gubjartsson, Kikinis & Jolesz 1997). The authors define a *linear isotropy* c_l, a *planar isotropy* c_p, and an *isotropy* c_s as

$$c_l = \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2 + \lambda_3} \tag{4}$$

$$c_p = \frac{2(\lambda_2 - \lambda_3)}{\lambda_1 + \lambda_2 + \lambda_3} \tag{5}$$

$$c_s = \frac{3\lambda_3}{\lambda_1 + \lambda_2 + \lambda_3} \tag{6}$$

The measures fall in the range $[0, 1]$ and sum up to 1 and define therefore a barycentric space of anisotropies.

3 Previous Work

Most researchers have concentrated their efforts onto the 3D reconstruction and visualization of nerve fiber tracts. An extensive survey is given in (Wünsche 2003).

Diffusion tensor fields in the medical field have been originally visualized in two dimensions by representing a derived scalar measure over a data slice with a colour map or a gray scale map (Pierpaoli et al. 1996). Subsequent research has examined the visualization of directional tensor information over 2D slices via colour mapping (Jones, Williams & Horsfield 1997, Pierpaoli 1997). Peled et al. visualize a slice of a diffusion tensor data set by indicating the in-plane component of the principal diffusion with a blue line and the out-of-plane components by colours ranging from green through yellow to red (Peled, Gudbjartsson, Westin, Kikinis & Jolesz 1998).

An interesting visualization of DTI slice images has been developed by Laidlaw et al. using concepts from oil painting (Laidlaw, Ahrens, Kremers & Readhead 1998). The projection of the principal diffusion direction onto the image plane is encoded by the stroke direction and the out-of-plane component by the saturation of the red colour component. Diffusion anisotropy is represented by the length/width ratio and transparency of brush strokes and the magnitude of the diffusion rate by the stroke texture frequency. Additional information is given using the lightness of the under-painting and an underlying checkerboard spacing.

4 Colour Mapped Surfaces

Medical imaging data is frequently displayed as a set of slices parallel to one of the coordinate planes. Regions of gray matter, white matter, and CSF can be displayed simultaneously using the segmentation function

$$\lambda_s = \begin{cases} 1 & \text{if } \lambda_{aniso} \geq 0.25 \text{ and } 5{*}10^{-6} < \lambda_{mean} < 10^{-3} \\ 2 & \text{if } \lambda_{mean} \geq 10^{-3} \\ 3 & \text{if } \lambda_{aniso} < 0.25 \text{ and } 5{*}10^{-6} < \lambda_{mean} < 10^{-3} \\ 0 & \text{otherwise} \end{cases}$$

The conditions for the values 1,2, and 3 are similar to the ones suggested by Pierpaoli et al. (Pierpaoli et al. 1996) and are chosen so that they indicate white matter, CSF and gray matter, respectively. Figure 1 (a) shows the resulting segmentation using the colours red, green and blue, respectively. In contrast to the previous images this image allows the identification of the thalamus as the two blue regions between the lateral ventricle in green and the internal capsule in red.

Regions of predominant linear anisotropic, planar anisotropic and isotropic diffusion are identified by using a barycentric colour map which is constructed by assigning three different colours to the vertices of a triangle and by interpolating these colours for each point P inside the triangle ΔABC using the barycentric coordinates

$$\alpha = \frac{area(\Delta PBC)}{area(\Delta ABC)}\ ,\ \beta = \frac{area(\Delta PCA)}{area(\Delta ABC)}\ ,\ \gamma = \frac{area(\Delta PAB)}{area(\Delta ABC)}$$

The barycentric coordinates define the weights of a convex sum of the triangle vertices which is equal to P, i.e., $\alpha A + \beta B + \gamma C = P$ where $0 \leq \alpha, \beta, \gamma \leq 1$ and $\alpha + \beta + \gamma = 1$. The measures defined by equations 4–6 define a barycentric space of anisotropies and therefore can be visualized by mapping them using the barycentric colour map.

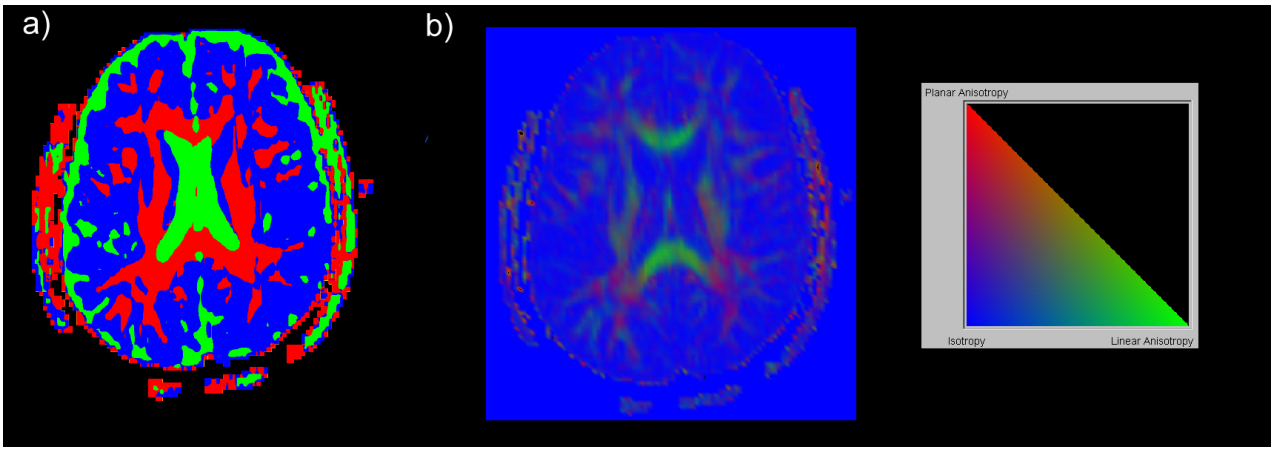

Figure 1: Horizontal slice (number 20) coloured using a segmentation function (a) and a barycentric colour map (b). In (a) red, green and blue indicate white matter, CSF and grey matter, respectively.

Figure 1 (b) indicates that the diffusion is predominantly linear in the genu and splenium of the corpus callosum and in the internal capsule, and more planar in the optic radiation and in the more peripheral white matter regions. A higher linear anisotropy indicates a higher alignment of nerve fibers.

5 Ellipsoid-based Textures

Informative textures can be created by colour mapping diffusion ellipsoids with directional information and/or anisotropy measures.

Textures are perceptually characterized by the spatial frequency, contrast and orientation of texture components (Schiffman 1996, Ware & Knight 1995). In order to make use of the pattern recognition capabilities of the human visual system we use a dense distribution of colour mapped tensor ellipsoids and scale them such that they overlap in regions of high mean diffusivities. As a result regions of CSF exhibit an irregular pattern consisting of the visible sections of overlapping ellipsoids, white matter regions are characterized by regularly arranged long cigar shaped ellipsoids aligned along the nerve fiber tracts, and gray matter regions are represented by small approximately spherical ellipsoids. We encode additional information and further differentiate the textural appearance of regions with different tissue type by using two types of colour maps and by choosing black as a background colour.

White matter regions and the direction of nerve fiber tracts are emphasized by using the spherical colour map shown in figure 2. The hue, saturation and brightness of the colour spectrum vary along the circumferential, longitudinal and radial directions of the sphere, respectively. We encode the direction of the maximum diffusivity by computing its spherical coordinates and by associating them with the hue and saturation of the colour map. The diffusion anisotropy λ_{aniso} is mapped onto the brightness parameter of the colour spectrum.

The results of applying this colour map to an ellipsoid-based texture are illustrated in figure 3. The visualization represents a horizontal slice through the brain. The colour mapped ellipsoids are illuminated using ambient and diffuse illumination. The image on the right shows a detail view of the image on the left.

We experimented with alternative illumination options and found (Wünsche 2003) that specular illumination makes it difficult to differentiate tissue types

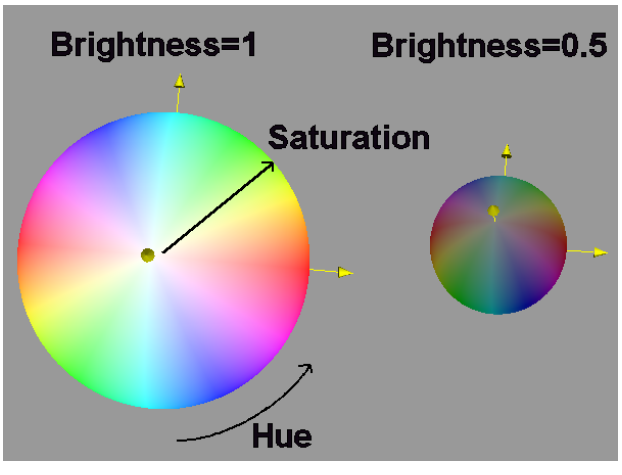

Figure 2: A spherical colour map with hue, saturation and brightness varying along the circumferential, longitudinal and radial direction of the sphere, respectively. The illustration shows the surfaces of the colour map formed by choosing a constant brightness parameter of 1.0 (left) and 0.5 (right).

since specular highlights dominate the image and obscure the ellipsoid colour and the different texture patterns generated by overlapping/non-overlapping ellipsoids. Using ambient illumination only results in the best differentiation between tissue types: gray matter appears black, CSF appears as regions with large overlapping darkly coloured ellipsoids and white matter is represented by elongated ellipsoids with a highly saturated colour. However, using ambient illumination only makes it difficult to perceive the 3D shape of individual ellipsoids. Using ambient and diffuse illumination as shown in figure 3 combines both good shape perception and good differentiation of tissue types.

An alternative visualization is obtained by colouring diffusion ellipsoids with the barycentric colour map introduced in section 4. As a result regions of isotropic, planar anisotropic and linear anisotropic diffusion are represented by spherical blueish, flat reddish and elongated greenish ellipsoids, respectively. Figure 4 shows an example rendered with a low diffuse and specular illumination. In order to emphasize fiber tracts the diffusion anisotropy is colour mapped

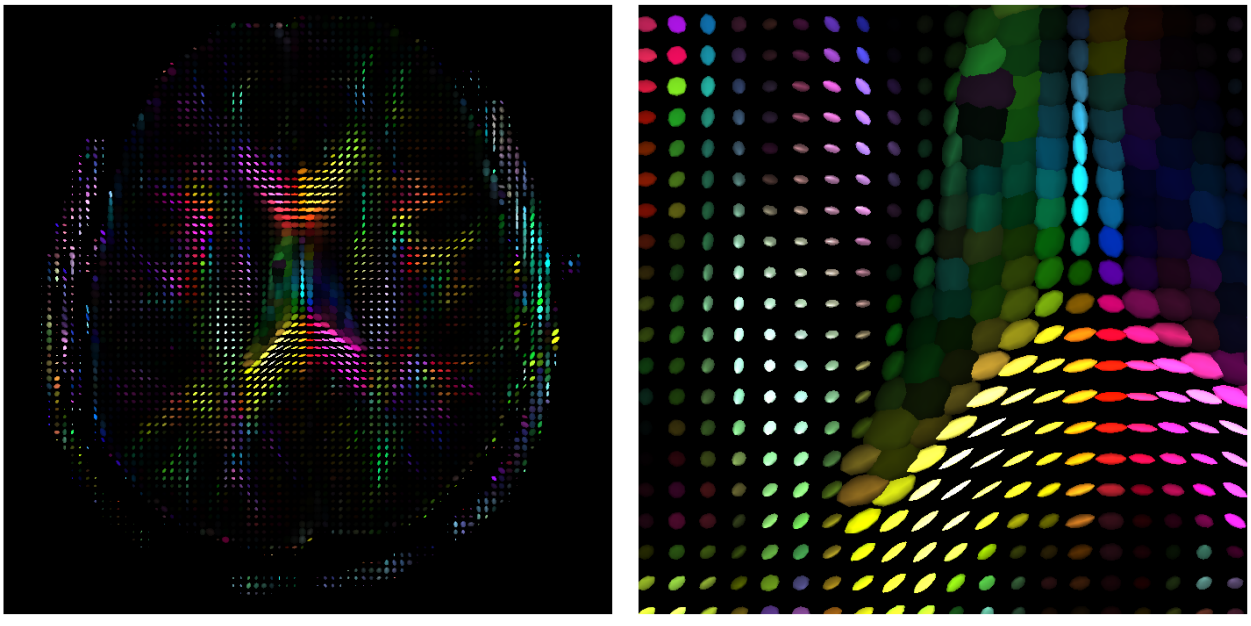

Figure 3: Fiber tract direction over a horizontal slice through the brain visualized using an ellipsoid-based texture. The ellipsoids are colour mapped with the spherical colour map in figure 2 and illuminated using ambient and diffuse illumination. The image on the right shows an enlargement of the region containing the splenium of the corpus callosum.

using a exponential colour map with low saturation and brightness which improves contrast to the shaded ellipsoids.

6 Anisotropy Modulated Line Integral Convolution

Disadvantages of the ellipsoid-based textures are that ellipsoids visualize the diffusion direction and hence the nerve fiber direction only at individual points, that the 3D shape of ellipsoids can be hard to perceive, and that there is little perceptual continuity between ellipsoids aligned along a nerve fiber tract. As an improved method for visualizing the fiber direction in DTI slice images we propose *Anisotropy Modulated Line Integral Convolution* (AMLIC). A 2D AMLIC texture can be described in simple words as a blend of a Line Integral Convolution (LIC) texture of the maximum diffusion direction with the colour mapped mean diffusivity.

Line Integral Convolution (LIC), originally proposed by Cabral and Leedom (Cabral & Leedom 1993), is an effective method to visualize vector fields by using curvilinear filters to locally blur an input noise texture I along a vector field $\mathbf{v}$.

An AMLIC texture is created by first computing the LIC texture from the maximum diffusion direction. As explained in the introduction nerve fiber tracts are characterized by a relatively high and anisotropic diffusion in the fiber direction. It is therefore possible to extract nerve fiber tracts as streamlines by integrating in the direction of the maximum diffusivity in regions of high anisotropy (Basser 2000). The LIC texture is defined by convolving a white noise texture with the maximum diffusion direction. This is achieved by tracing through the centre of each output texture pixel a short streamline along the maximum diffusion direction projected onto the image plane. The intensity of the output texture pixel is the sum of the intensities of the input texture pixels along that streamline weighted with the integral of the convolution kernel which in our case is a simple box filter. The length of the convolution kernel at a pixel is proportional to the angle between the maximum diffusion direction and the textured surface. Since anisotropic diffusion can also be registered due to noise or eddy currents in fluid filled compartments the maximum diffusivity at any step during the streamline integration must exceed a certain predefined limit and the streamline must exceed a specified minimum length and must be sufficiently smooth.

The LIC texture is colour mapped with the diffusion anisotropy and for each pixel a blending factor monotonically increasing with the diffusion anisotropy is defined. We obtained good results by using a power function with the exponent 0.2. More details are found in (Wünsche 2003). The LIC texture is blended with the colour mapped mean diffusivity using the OpenGL "GL_BLEND" operation (Woo, Neider & Davis 1997). The texture colour of pixel (i, j) is then given by:

$O_{ij} = \alpha_{ij} C_{ij} + (1 - \alpha_{ij}) D_{ij}$
`// the output texture colour`

`where`

$C_{ij} = L_{ij} c(\lambda_{aniso}(i,j))$ `// the LIC texture`
`// colour mapped with the diffusion`
`// anisotropy at the pixel centres`
L_{ij} `// the LIC texture obtained from the`
`// principal diffusion direction`
$D_{ij} = d(\lambda_{mean}(i,j))$ `// a texture representing`
`// the colour mapped mean diffusivity`
$c(t), d(t)$ `// colour spectra indexed`
`// with` $t \in [t_{min}, t_{max}]$
$\alpha_{ij} = (\lambda_{aniso}(i,j))^{0.2}$ `// a blending`
`// factor monotonically increasing`
`// with the diffusion anisotropy`

The resulting texture has three properties: regions of high anisotropy feature a LIC like texture which indicates the 3D nerve fiber direction. Long texture elements indicate nerve fibers tangential to the textured surface whereas very short point-like texture

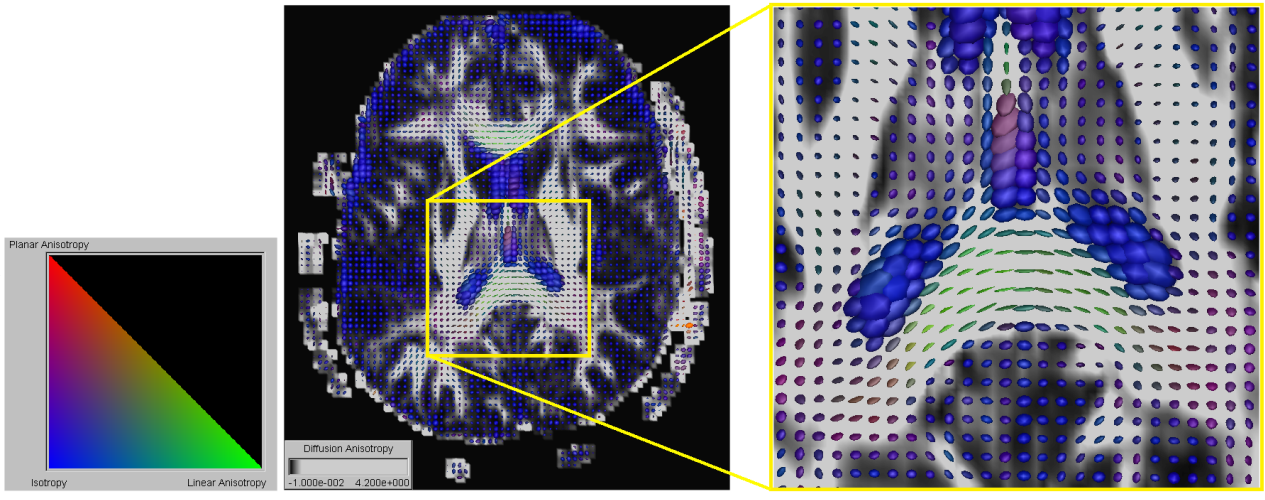

Figure 4: Fiber tract direction over a horizontal slice through the brain visualized using an exponential colour map and an ellipsoid-based texture obtained by using the barycentric colour map shown on the left hand side of the figure.

elements indicate nerve fibers almost orthogonal to the textured surface. Regions which are not textured have a low anisotropy and therefore represent either gray matter or cerebral spinal fluid. If an appropriate colour map is chosen (we found that three equally distributed colours over the range of scalar values of the mean diffusivity work well) then gray matter is indicated by the colour(s) associated with low values of the mean diffusivity and CSF is indicated by the colour(s) associated with high values of the mean diffusivity.

Note that by blending the LIC texture and the colour mapped mean diffusivity we take into account the fact that there is no clear-cut boundary between white matter and gray matter. The resulting visualization therefore has advantages over image segmentation methods.

An example is given in figure 5. The cyan and green regions represent areas of high mean diffusivity and low anisotropy and therefore indicate fluid filled compartments. The whitish regions represent areas of low anisotropy and low mean diffusivity and therefore indicate gray matter. Textured regions exhibit a high anisotropy and indicate white matter. Very long texture components indicate fiber tracts parallel to the image plane, e.g., in the splenium of the corpus callosum (1). In contrast a noise-like texture with very short texture components indicates fiber tracts almost orthogonal to the image plane, e.g., in the posterior limb of the internal capsule (2).

7 Conclusion

Visualizing the diffusion tensor field in the brain gives an in vivo view of anatomical structures which was previously unobtainable. New insight into diffusion tensor data is gained using barycentric colour maps which show the distribution of anisotropies over a region and indicate possible fiber tract crossings. Ellipsoid-based textures provide a visualization of fiber direction and tissue types or anisotropy properties. A high amount of information can be encoded into slice images using anisotropy modulated line integral convolution. The technique does not only indicate three dimensional fiber direction but also provides a visual segmentation of tissue types.

8 Future Research

In future we intend to use the presented techniques for the exploration of various white matter diseases. Current research indicates that DTI is superior to traditional MRI imaging and using our advanced visualization methods might help to better understand the development of various white matter diseases and the anatomical abnormalities in neurological disorders such as schizophrenia. Ideally we would like to obtain a series of data sets taken over time which makes it possible to create an animated visualization of the progress of a neurodegenerative disease.

We are also interested in qualitatively comparing our simple streamline tracking algorithms with specialised methods based on Markov-chain models and diffusion-advection processes.

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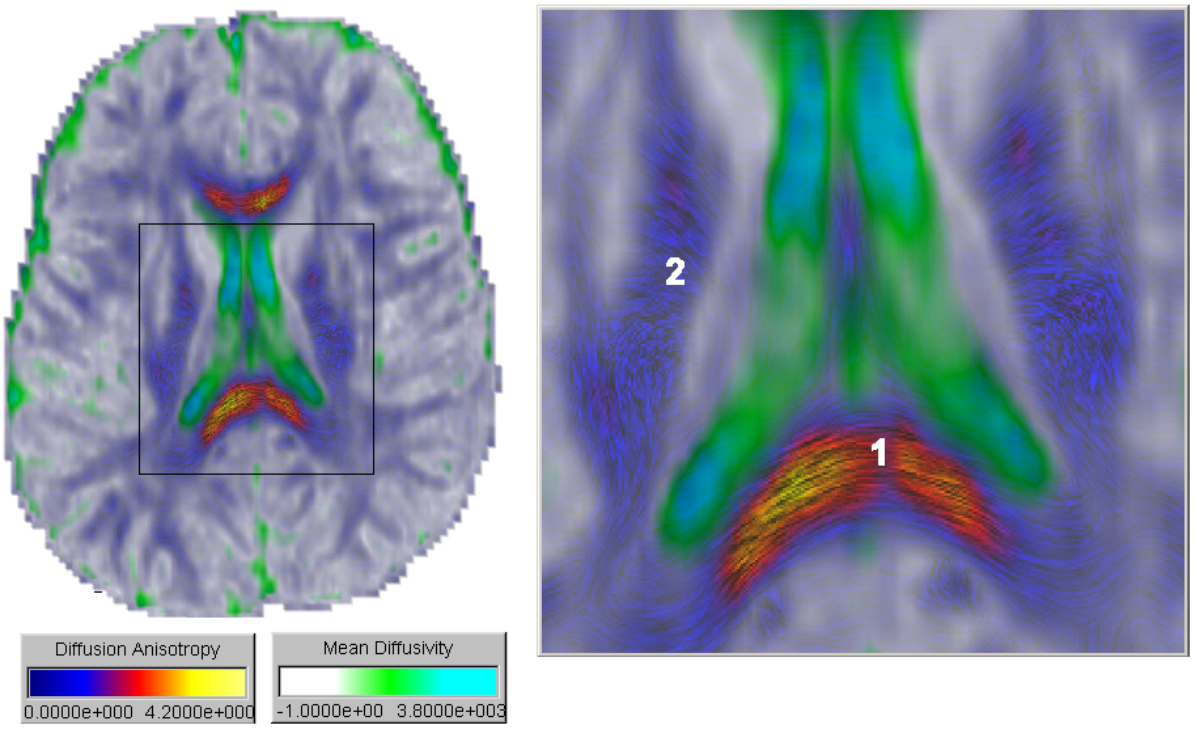

Figure 5: Fiber tract direction over a horizontal slice through the brain visualized using anisotropy modulated line integral convolution (AMLIC). The nerve fibers in the splenium of the corpus callosum are parallel to the image plane (1) whereas nerve fibers in the posterior limb of the internal capsule (2) are almost vertical to it.

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