Characterizing properties by fiber bundle parameters derived from the fODF

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Introduction

In Diffusion MRI (dMRI), spherical deconvolution [1] is used to model regions with complex micro-structure. The method produces a fiber orientation density function (fODF), which is represented using spherical harmonics coefficients. These parameters are usually difficult to interpret directly in terms of physical properties. Often the fODF can be viewed as superposition of multiple peaks, each associated to an approximately collinear fiber bundle. By parameterizing each of these fODF peaks using a scaled Bingham distribution we were able to characterize the underlying fiber bundles and capture their second-order statistics. In addition, the integral of the fODF over the unit sphere corresponds to the total number of fibers contained in a single voxel. By integrating each of the scaled Bingham distributions we estimated the relative number of fibers corresponding to each bundle. For example, comparing this integral for the first two largest peaks yields a measure for the complexity of the underlying micro-structure.

Methods

- High resolution dMRI scans were acquired on a Siemens 3T TIM Trio scanner (1.5mm isotropic, 60 directions, b=1000s/mm², 32-channel array head coil, GRAPPA 3, AV=3) from a single healthy subject.
- We calculated the signal attenuation by dividing the image by the b0 image to remove the T2 influence.
- We then obtained the kernel from voxels containing a single parallel fiber population, i.e. voxels of the corpus callosum. This kernel was then corrected to represent the signal of a single fiber, assuming a fiber density of 380 000 fibers/mm², i.e. 855 000 fibers/voxel. However the approximation of the fODF using spherical harmonics introduces a bias, which then has to be corrected to ensure the correct number of fibers to be represented in the kernel voxels.
- We performed an 8th order spherical harmonic approximation of the fODF using constrained spherical deconvolution (CSD)[5].
- We then estimated the parameters of one scaled Bingham distribution for each of the fODF maxima, assuming they represent separate fiber bundles. This was done via linear least squares fit using the peak neighborhood, while fitting the direction of the Bingham distribution with an orientation matrix [7,8].
- From this fit we directly estimated peak length, peak direction and peak spread. To compute the peak volume we integrated the scaled Bingham distribution over the unit sphere, estimating the number of fibers contained within the peak. Afterward we computed the quotient of the number of fibers for largest peak and the number of fibers within the three largest peaks. This was then used as measure for the structural complexity.

1

$$\psi(\vec{u}) = c \exp\left(k_1 \left(\vec{\mu_1} \cdot \vec{u}\right)^2 + k_2 \left(\vec{\mu_2} \cdot \vec{u}\right)^2\right)$$

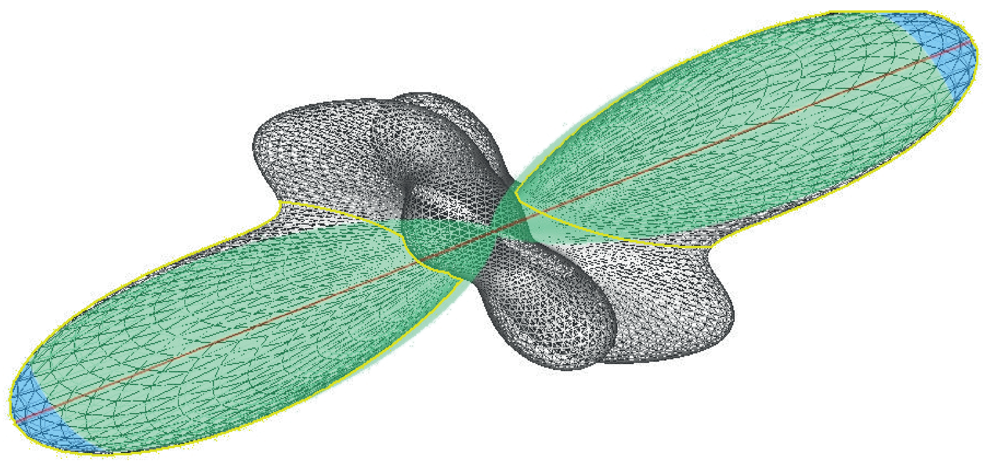
The scaled Bingham distribution.

Results

Metrics

- The apparent fiber count (AFC) is calculated by integrating the fODF over the sphere. This is equivalent to the first spherical harmonic coefficient corrected for the T2 contrast. It describes the number of fibers contained within a voxel.
- The apparent bundle fiber count (ABFC) is obtained by integrating the fitted Bingham distribution over the sphere. It gives the number of fibers contained within the bundle approximated by the corresponding Bingham distribution.
- Eccentricity is a measure of ovality of the fitted population. It is estimated from the concentration parameters of the Bingham distribution. It is zero in case of the profile being a circle and approaches one the more oval the profile gets.
- Structural complexity describes the degree to which the fiber configuration within a voxel deviates from a single, approximately collinear (allowing for some spread), fiber population. It is zero if a single fiber bundle is present and close to one in case of three bundles of about same size being present.

2 Schema of fitting the Bingham distribution to the fODF. The fODF is shown in light grey. The maximum direction its largest peak is visualized as red line. The directions of the Bingham distribution (green) are fitted using a small neighborhood of the maximum direction, which is shown in blue. The points which are used for the calculation of the concentration parameters are those within the area outlined in yellow.



The Bingham distribution can closely approximate the peaks of the fODF. This enables the separation of the fODF into compartments representing the underlying fiber structure, as well as deriving measures directly related to microanatomy from the fitted distribution, which therefore are easily interpretable. The two concentration parameters characterize the peak anisotropy and provide a measure for the fiber spread. As an example figure 2 shows an approximation of the structural complexity computed from the ratio of the peak amplitudes compared to the tensor FA. The integral over the scaled distribution quantifies the relative contribution of the different compartments and is directly described by the scaling parameter. The representation of the fiber populations by Bingham distributions allows for the representation of measures for each fiber bundle separately, thereby describing the influence a single bundle has on the measure.

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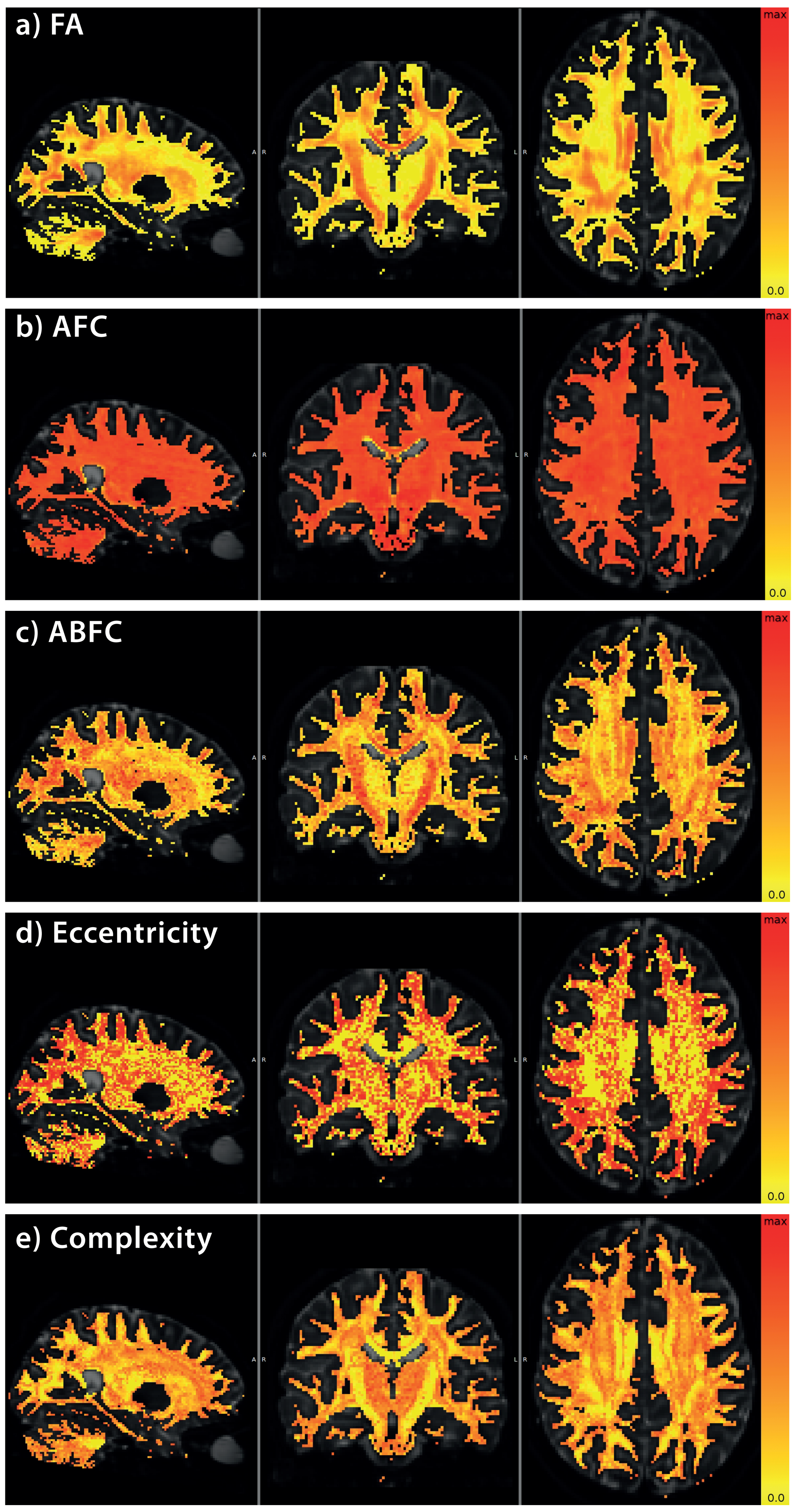

This image depicts the FA, which has a Range from 0 to 1. It is sensitive to structural changes, however, this leads to loss of specificity which we tried to increase using metrics derived from the Bingham fit.

The AFC is relatively constant over the whole brain. The maximum value used in the figure is the number of fibers of the voxels in the kernel, i.e. 855 000 fibers.

FA and ABFC seem closely connected, as one can observe a similar pattern. The maximum value is set to the 855 000 fibers which is the same number as for the AFC.

The eccentricity of the largest peak gets larger the closer one gets to the cortex. This indicates the fanning of fibers as they enter the gray matter.

In this map of the complexity one can identify areas in which several fiber bundles are present.

Conclusions

We addressed the problem of finding a robust parameterization of the fODF in order to separately characterize the fiber bundles contributing to the fODF, as well as deriving measures from this parameterization in a way that they are directly linked to the micro-architecture. We did this by imposing a Bingham distribution based model for the distribution of single fiber bundles. Overall our approximation of single-fiber peaks using a Bingham function supplies a powerful tool for parametric quantification of fiber bundle properties. The derived metrics allow for increasing the specificity of the FA because of their direct connection with the underlying fiber geometry, as well as being suited for directly deriving measures for microstructural properties.

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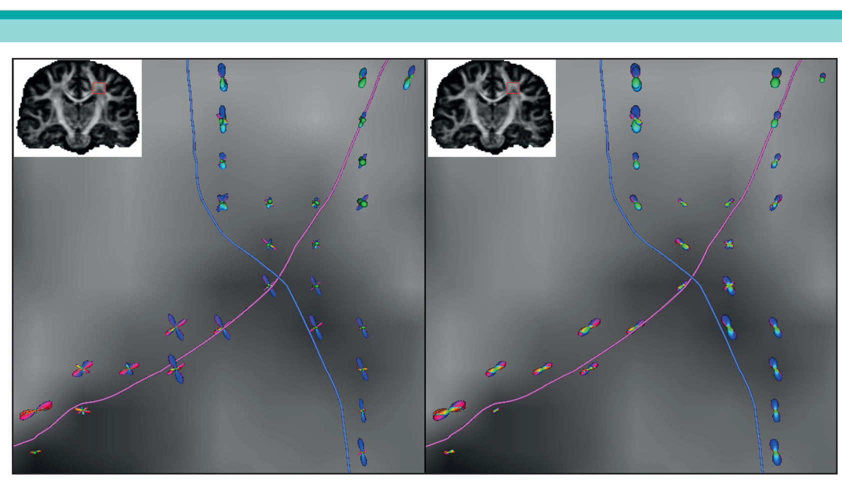

The mapping of the fODF to fiber bundles enables the investigation of fiber bundle properties (e.g. FA) along each pathway [9]. Left: Spherical deconvolution result in spherical harmonic Representation. Right: Bingham fit of fODF peaks for one transcallosal tract and a representative selection of the cortico-spinal tract crossing in a coronal section of the brain.

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