Quantification of fiber bundle properties using a decomposition of the fiber orientation distribution function

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Introduction:

In diffusion MRI (dMRI), one method used for modeling multiple fiber orientations in regions with complex microstructure is spherical deconvolution [1]. This produces a fiber orientation distribution function (fODF). Most often, this function represents a superposition of multiple peaks, each associated to one relatively coherent fiber population (bundle). By parameterizing these peaks one may be able to disentangle and separately characterize these bundles. In this line, the fODF peaks were approximated by Bingham distributions [2,3,4], which were scaled to the size of the respective maximum and capture second-order statistics of the fiber orientations. Using a geometry-based fitting approach we approximated the three largest peaks of the fODF, which correspond to the three largest fiber populations within the voxel. These were then used for deriving measures for fiber properties, which can be assigned to distinct fiber populations within each voxel.

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 healthy subject and on a Siemens 3T VERIO scanner (1.7mm isotropic, 60 directions, b=1000s/mm², 32-channel array head coil, GRAPPA 2, AV=1) from a tumor patient. We performed a 6^{th} order spherical harmonic approximation of the fODF. This was done using the diffusion attenuation signal and a corresponding kernel function estimated from voxels with an FA value of 0.8 or greater. Assuming each of the fODF maxima represents a single fiber peak, we estimated the parameters of a scaled Bingham distribution modeling the underlying fiber bundle.

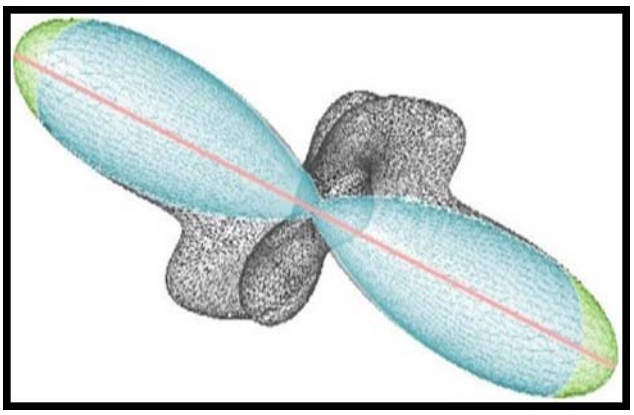

Figure 1: The grey glyph in the background depicts the fODF. The maximum direction is shown as a red line. The green areas show the peak neighborhood of the maximum used for fitting. The fitted Bingham distribution is shown in blue.

As the fODF represents the angular density of fibers, its integral over the sphere corresponds to the total number of fibers per voxel, thus approximating spatial fiber density. Interestingly, the first coefficient of the spherical harmonics, analogously to the Fourier transform, corresponds to the integral of the function over the unit sphere, thus approximating spatial fiber density as well. The separation into scaled Bingham distributions now allows us to estimate the integral of each underlying fiber population separately. This leads to a measure, which states how much of the total fiber density can be explained by the separate fibers contained within each voxel.

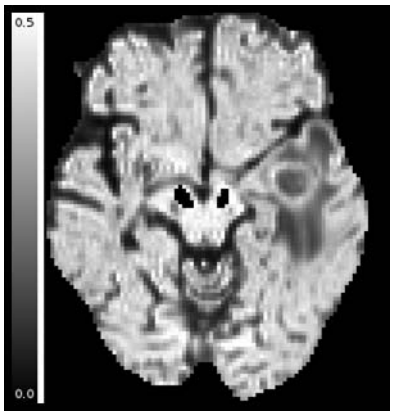

Figure 2: The integral of the fODF over the unit sphere, which approximates the spatial fiber density, is shown in this image of a tumor brain.

Results:

The Bingham distribution can closely approximate the peaks of the fODF. The scaling parameter of the distribution quantifies the relative contribution of the different compartments and from this the integral over the scaled Bingham distribution can easily be derived. The two concentration parameters of the Bingham distribution characterize the peak anisotropy and provide a measure for the spread of fiber compartments revealing either a circular shape of the distribution e.g. in the corpus callosum, or a fanning of the fibers of the major peak, as, e.g., in the internal capsule. The first spherical harmonic coefficient of the fODF was used as a measure for the spatial fiber density. In order to quantify this measure we examined the fODF within a tumor brain. As expected the density within the tumor as well as in the surrounding oedema is significantly lower than in the white matter. In order to use this measure for quantification a more complex diffusion model is necessary. The representation of the fiber populations by Bingham distributions allowed for the representation of measures for each fiber bundle separately, thereby describing the influence a single bundle has on the measure.

Conclusions:

The approximation of single-fiber peaks using a Bingham distribution supplies a powerful tool for parametric quantification of fiber bundle properties which might replace measures derived from the diffusion tensor (e.g. FA) in areas of crossing fibers. Combination with properties of the fODF enables separating the influences these single bundles have on a measure. For more accurate results there are two major improvements we are currently working on, first dealing with the problem of overlap of the fitted Bingham distributions, second incorporating a more complex diffusion model, which accounts for the interdependence between T2 relaxation (thus b_0) and the diffusivity.

[1] Tournier et al, Neuroimage 23, 2004. [2] Seunarine et al, ICCV, 2008. [3] Kaden et al, Neuroimage, 2007. [4] Bingham, Ann Stat, 1974.