Advanced Fiber Tracking Using ODF Based Force Fields

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Introduction

High angular resolution diffusion-weighted imaging techniques, such as diffusion spectrum imaging [1] and q-ball imaging (QBI) [2], have been developed to resolve complex intravoxel fiber structure. Thereby, the entire diffusion profile is captured in the so-called orientation distribution function (ODF). Advanced fiber tracking methods utilize the ODF to detect local diffusion maxima [3,4], to promote the evolution of a wave front [5] and to determine connection weights through volume ratios [6]. In this work, the ODF is converted voxel-by-voxel into a force field and the motion of particles, exposed to this force field, is simulated. The computed paths of the particles are tracked and exploited for the generation of connectivity maps and virtual fiber networks.

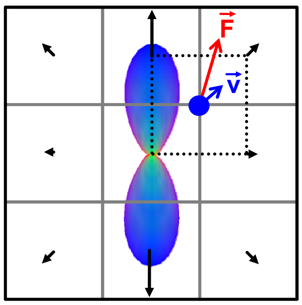

Figure 1: An ODF and the corresponding vector field in a single voxel depicted in 2 dimensions. A simulated particle (blue dot) with its velocity vector and the interpolated force vector is overlaid.

Methods

From ODF to force field: ODFs were reconstructed using the QBI approach in combination with spherical harmonics [7]. To transform the ODFs into a force field, each voxel was subdivided into 3x3x3 sub-voxels. In the next step, a radial force vector was assigned to each subvoxel with a force value equal to the normalized ODF value in this direction (see Fig. 1).

Simulation of particle motion: 10'000 particles were placed randomly in a region of interest (ROI). The particles were then exposed to the force field and their position and velocity was iteratively updated using principles of classical mechanics:

$$v' = v + t \cdot \frac{F}{m} - d \cdot v \quad \text{and} \quad x' = x + t \cdot v'$$

, where *m*, *x* and *v* are the particle's mass, position and velocity, respectively, *t* corresponds to the time step, *F* to the force that acts on the particle and *d* denotes the damping factor. In this work, the particles mass was set to unity while the time step and the damping factor were iteratively optimized so that the particle undergoes the influence of each force vector on its course through the dataset. The force *F* was determined by interpolating the eight nearest force vectors (see Fig. 1). Thereby, the generalized fractional anisotropy (GFA) index [7] serves as an indicator for the direction of the interpolated forces. An attractive force was assigned to each subvoxel featuring a GFA above 0.4, while a repulsive force was assigned to subvoxels with a GFA below 0.4 to prevent the particles from entering voxels with an isotropic diffusion profile. Virtual fibers were generated by tracking each particle's path. Furthermore, a probability was assigned to each voxel by counting the number of particles passing through that voxel divided by the whole number of simulated particles within the seed ROI.

Data acquisition: Data were acquired on the Philips Achieva 3T system (Philips Healthcare, Best, the Netherlands) using a diffusion-weighted single-shot spin-echo EPI sequence with the following scan parameters: FOV = 160 x 184 mm^2, matrix = 92 x 90, reconstruction matrix = 96 x 96, 10 contiguous slices, slice thickness = 2 mm, SENSE reduction factor = 2, TE = 55.6 ms. Diffusion-weighted images were acquired along 128 directions distributed uniformly on a sphere with a maximum b-factor of 3000 s/mm^2, complemented by one scan with b = 0 s/mm^2.

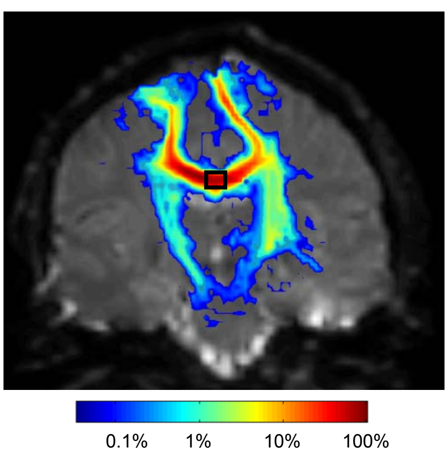

Figure 2: Connectivity map with a seed ROI (black square) in the body of the corpus callosum overlaid onto the non-diffusion-weighted image.

Results

Figure 2 shows the connectivity maps for a seed ROI placed in the body of the corpus callosum. The colormap represents the probability of connection ranging from red (high) to blue (low). The particle's paths are visualized in Figure 3. The used color-coding scheme shows connections from left to right in red, connection from top to bottom in blue and through plane connections in green.

Discussion and Conclusion

The presented method allows transforming the ODF map of a QBI dataset into a vector field which provides a simulation setup for particles. The course of the particles, evolved by Newton equations, is traced and converted into connectivity maps and virtual fibers. Using the force field, the presented method circumvents the intricate post-processing step of ODF maxima detection typically required by advanced tracking algorithms [3,4].

In conclusion, a novel QBI based advanced fiber tracking algorithm was introduced using an ODF-derived vector field and simulation of particle motion.

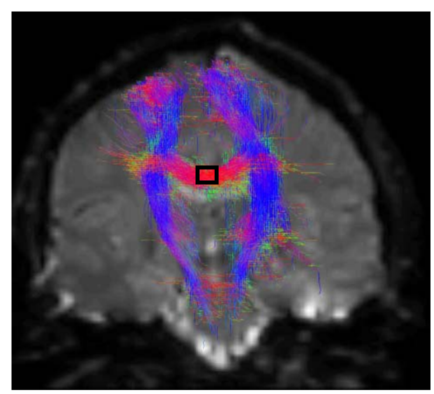

Figure 3: Reconstructed virtual fibers based on the particle's paths overlaid onto the non-diffusion-weighted image. The seed ROI in the corpus callosum is depicted by a black rectangle.

References

[1] Wedeen, V.J. et al., [2005], MRM, 54(6): 1377-1386. [2] Tuch, D.S., [2004], MRM, 52: 1358-1372. [3] Wedeen, V.J. et al., [2008], NeuroImage, 41: 1267-1277. [4] Sotiropoulos, S.N. et al., [2010], NeuroImage, 49: 2444-2456. [5] Campbell, J.S.W. et al., [2005], NeuroImage 27: 725-736. [6] Iturria-Medina, Y. et al., [2007], NeuroImage 36: 645-660. [7] Hess, C.P. et al., [2006], MRM, 56: 104-117. [8] Descoteaux, M. et al, [2007], MRM, 58: 497-510.