A multi-structural Fiber Crossing Anisotropic Diffusion Phantom for HARDI reconstruction techniques validation

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Introduction

There is significant interest in evaluating the performance and reliability of white matter fiber tractography algorithms. Diffusion tensor imaging (DTI) approach [1] is a powerful tool for non-invasive investigation of microstructure and has been successfully applied to detect different white matter diseases [2]. DTI-based fiber tracking gives insights into the complex architecture of the brain. However, it is well known that it presents a number of limitations, especially in presence of fiber crossing, suggesting the development of new algorithms based on non-parametric reconstruction techniques (HARDI [3-7]). The validation of fiber reconstruction by these different approaches remains challenging and requires suitable test phantoms. For isotropic diffusion, the ADC can be well verified on pure spherical water phantoms, whilst the use of simulated data is limited by the fact that no real MRI data are considered, with particular regard to the presence of normal imaging artifacts, noise characteristics, and voxel size limitations. These aspects have suggested the realization of an experimental model with different fiber crossing configurations (PIVOH, Phantom with Intra-Voxel Orientation Heterogeneity), able to simulate the structural complexity of the white matter, in correspondence of fiber intersection.

Materials & Methods

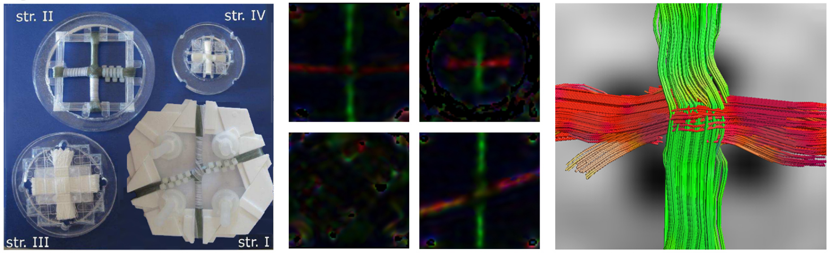
PIVOH was built in modular way with several configurations, diversifying for geometry and material, in order to evaluate the reconstruction of fiber bundles at different levels of anisotropy and different types of crossing. It presents four different structures, enclosed in a poliver box (diamagnetic material) with a airtight closure. Figure 1.a shows the four different structures and Table 1 lists their correspondent features. Fibers of structures I, II and IV are made in nylon (impermeable), whilst those of structure III are realized by hollow filaments (permeable). The structures in nylon reproduce a situation of hindered diffusion, whilst the structure III replicates a restricted diffusion state [8]. In order to reduce the susceptibility artifacts, the phantom was filled with distilled water using a vacuum process to forbid the creation of air bubbles between adjacent fibers. All diffusion weighted images were acquired using a 1.5 T MR system (Signa Horizon LX, GE Medical System) and an interleaved single-shot pulsed field gradient spin-echo sequence. Two datasets were collected with different MR parameters. The first was registered in order to evaluate the analysis based on the diffusion tensor imaging, using 25 directions of diffusion gradients (TR/TE=11000/106 ms, b-value=1000 s/mm^2, FOV=19cmx19cm, matrix=64x64, NEX=2, 28 slices, slice thickness=3mm), whilst the second dataset was collected applying 55 directions of diffusion gradients (TR/TE=4000/106 ms, b-value=1500 s/mm^2, FOV=19cmx19cm, matrix=64x64, NEX=2, 12 slices, slice thickness=3mm positioning three slices for each structure) in order to perform Q-Ball reconstruction of the fiber tracts. Data analysis was performed by a Matlab code for the calculations of diffusion invariants and the Trackvis software package for fiber tracking.

Results

The structures realized in nylon fibers (structure I, II e IV) show detectable values of FA along the fibers tracts, whilst the structure III does not present significant values of FA even in correspondence of the bundles. Moreover, among all the structures, structure IV provides higher values of FA and thus, it appears to assure a better directionality of the fiber bundles, especially in the areas closer to the crossing zone. Figure 1.b shows the Directional-Encoded Color (DEC) map of an axial slice for each fiber structure.

In order to evaluate the performances of the different techniques of fiber reconstruction, the structure IV seems to be the more appropriate for further studies. In particular, Figure 1.c shows the reconstruction of fiber bundles of this configuration, obtained by the non-parametric method Q-Ball. The fiber tracking shows how the fiber bundles are well reproduced also in the crossing zone, thanks to the ability of this method of resolving the Orientation Distribution Function, ODF, finding more local maxima.

Figure 1



(a) (b) (c)

Table 1

Structure	Material of fibers	Diameter of fibers (μm)	Crossing (degrees)
I	nylon	200	77
II	nylon	200	90
III	polysulfone	180-230	90
IV	nylon	60	90

Conclusion

In conclusion, the experimental model PIVOH seems to be a useful tool for the study of methods devoted to the resolution of the fiber-crossing problem. In particular, it could be easily exploited in validation of new techniques of both acquisition and reconstruction of diffusion MR data, as well as in fiber tracking algorithms application. This feature is more evident for structure IV where its smaller diameter allows the achievement of higher directionality, since the dimensions of the realized compartments are comparable to the free quadratic random walk of water molecules. On the contrary, the relative bigger inner diameter of hollow fibers in structure III produces the opposite result (low directionality and low FA values).

References: [1] Basser, Jones NMR Biomed. 2002; 15:456-467. [2] Ben Bashat at al. Neuroimage 2007; 37(1):40-47. [3] Tuch MRM 2002; 48:577-582. [4] Wedeen MRM 2005, 54:1377-1386. [5] Tuch MRM 2004, 52:1358-1372. [6] Jansons Inv Problems 2003, 19:1031-1046. [7] Tournier NeuroImage 2003, 20:276-288. [8] Assaf MRM 2004; 52:965-978.