A High Angular Resolution Diffusion Imaging (HARDI) Template of the Human Brain

A. Varentsova[1], S. Zhang[2], and K. Arfanakis[2]
[1]Biological, Chemical and Physical Sciences, Illinois Institute of Technology, Chicago, IL, United States, [2]Biomedical Engineering, Illinois Institute of Technology, Chicago, IL, United States

Introduction: High Angular Resolution Diffusion Imaging (HARDI) is a powerful extension of diffusion MRI. Unlike diffusion tensor imaging (DTI), HARDI is capable of resolving crossing, branching and kissing fibers, which is especially crucial for studies of brain connectivity. Development of a HARDI template of the human brain may allow the development of a detailed atlas of the microarchitecture and connectivity of the human brain. Also, a HARDI template may be used as a reference in comparisons of the microstructural integrity and brain connectivity across populations. However, the long scan-time of HARDI acquisitions, especially when combining HARDI with pulse-sequences that minimize image artifacts (such as Turboprop), as well as the complexity of high-dimensional, non-linear, inter-subject spatial normalization of HARDI datasets, render the development of a HARDI template from a large number of subjects rather problematic. In contrast, the efficiency of low angular resolution diffusion imaging in terms of scan-time allows combination with multi-shot pulse-sequences that minimize artifacts. Also, the information generated from low angular resolution diffusion imaging is rich enough to allow inter-subject spatial normalization at high detail (e.g. diffusion tensor-based registration). Therefore, the purpose of this study was to develop a HARDI template of the human brain by appropriately combining information from multiple artifact-free datasets collected with low angular resolution diffusion imaging on 67 subjects.

Methods: Data and Preprocessing: Turboprop diffusion-weighted (DW) (12 diffusion directions [Minimum Energy scheme] with b=900s/mm^2) and non-DW data (2 volumes with b=0s/mm^2) were acquired on a 3T GE MRI scanner from the brain of 67 healthy subjects [1]. Following brain extraction and motion correction, the diffusion tensors were estimated throughout the brain of each subject. The diffusion tensors from a single subject were non-linearly, spatially transformed to ICBM-152 space as described elsewhere [2]. The diffusion tensors from all 67 subjects were then registered to the single subject's data using deformable registration of diffusion tensors with explicit orientation optimization [3] (DTI-TK, PICSL, PA, USA). The resulting transformations were applied to the b=0s/mm^2 and DW data of the corresponding subjects. Thus, each voxel in ICBM-152 space contained 12 DW signals from each subject. Due to the different spatial transformations applied to each voxel of each subject, each voxel in ICBM-152 space contained 804 DW signals (67 subjects × 12 DW signals per subject) corresponding to 804 unique diffusion directions. These directions were different for each voxel, and were non-uniformly distributed in 3D space (Fig. 1). However, they provided DW information with high angular resolution for the combined dataset. DW signals were normalized to the b=0s/mm^2 signals from the corresponding subject before being included in the combined dataset. Also, outliers caused by noise or misregistration were removed. Less than 30% of the DW signals were rejected in each voxel.

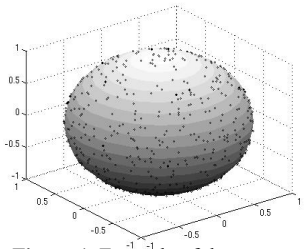

Figure 1. Example of the non-uniform distribution of diffusion directions in one voxel of the combined dataset.

Spherical Harmonics (SH) Decomposition: The orientation distribution function (ODF) was reconstructed in each voxel of the combined dataset as a series: $ODF(\theta,\varphi)=\sum_{j=1}^{R} 2\pi P_{lj}(0)u_j Y_j(\theta,\varphi)$ [4,5,6], where u_j: series coefficient; $P_{lj}(0)$: Legendre polynomial of degree l; $Y_j(\theta,\varphi)$: modified even, symmetric, real and orthogonal SH basis. Laplace-Beltrami regularization was used to reduce ODF estimation errors [6]. Finally, ODFs were min-max normalized and scaled by the generalized fractional anisotropy (GFA) [4].

Results: A map of computed ODFs in the midbrain can be seen in figure 2. This image shows the superior cerebral peduncle crossing the reticulospinal tract. Figure 3 shows a resolved ODF map in the corpus callosum containing both regions with single orientation and regions of intravoxel orientational heterogeneity.

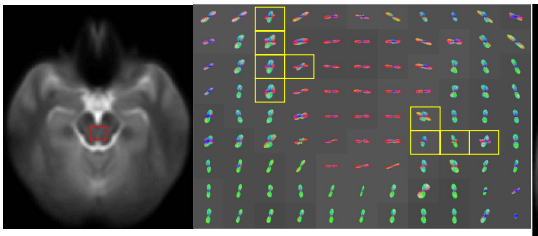

Figure 2. ODF map in the midbrain.

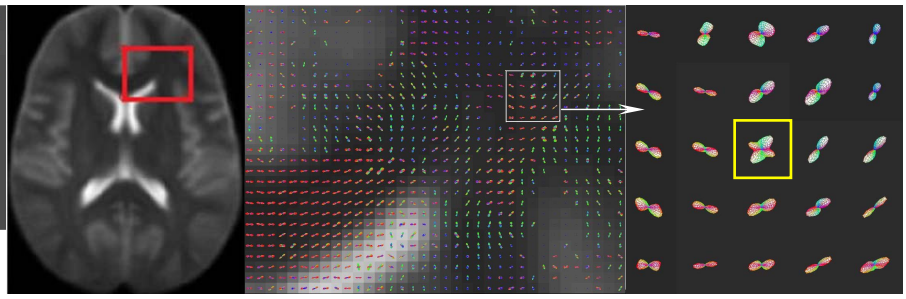

Figure 3. ODF map in frontal lobe white matter.

Discussion: This work presented a HARDI template of the human brain. To our knowledge, this is the first HARDI template developed to date. The template was produced by appropriately combining the DW signals from 67 low angular resolution diffusion datasets. This allowed the use of DW data from individual subjects collected with sequences that minimize image artifacts without excessively increasing the scan time. Extensive validation of the ODF information in the template is currently underway. Preliminary results suggest that the approach presented here allows resolution of intravoxel fiber crossings, and the information contained in the template is in agreement with underlying fiber anatomy of the human brain.

References: [1] Peng H, et al., Neuroimage 2009; 46:967-980. [2] Zhang S, et al., Neuroimage 2010; in press. [3] Zhang H, et al., Med Image Anal 2006; 10:764-785. [4] Tuch, MRM 2004; 52:1358:1372. [5] Descoteaux et al., MRM 2007; 58: 497-510. [6] Descoteaux et al., MRM 2006; 56: 395-410.