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

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## Introduction

High Angular Resolution Diffusion Imaging (HARDI) is a powerful extension of DTI capable of resolving intravoxel heterogeneity of fiber orientations which is important for brain connectivity studies. However, lengthy HARDI acquisitions, especially combined with pulse-sequences minimizing image artifacts, make the development of a HARDI template from a large number of subjects problematic. In contrast, scan-time efficiency of low angular resolution diffusion imaging allows combination with multi-shot pulse-sequences that minimize artifacts. The purpose of this study was to produce a human brain HARDI template by combining information from artifact-free low angular resolution datasets collected on 67 subjects.

## Methods

**MRI data acquisition:** Turboprop diffusion-weighted (DW) (12 diffusion directions, 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].

**Preprocessing**:
•Diffusion tensors were estimated throughout the brain of each subject.
•Single subject's tensors were non-linearly, spatially transformed to ICBM-152 space[2].
•Tensors from all 67 subjects were registered to the single subject's data using deformable registration with explicit orientation optimization (DTI-TK)[3].
•Resulting transformations were applied to the data (non-DW and DW) of the corresponding subjects.
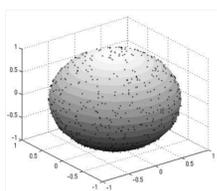


**Fig.1.** Example of the non-uniform distribution of diffusion directions in one voxel of the combined dataset.

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 contained 804 DW signals (67 subjects × 12 DW signals per subject) corresponding to 804 unique diffusion directions. These directions are different for each voxel and non-uniformly distributed in 3D space [Fig.1], thereby providing DW information with high angular resolution for the combined dataset.

**Spherical Harmonics (SH) Decomposition:** The orientation distribution function (ODF) was reconstructed in each voxel of the combined dataset as a series:

$$ODF(\theta,\varphi) = \sum_{j=1}^{R} 2\pi P_{lj}(0) u_j Y_j(\theta,\varphi) \qquad Y_j(\theta,\varphi) = \begin{cases} \sqrt{2}\cdot\mathrm{Re}(Y_k^{|m|}) & if -k \le m < 0 \\ Y_k^0 & if\ m = 0 \\ \sqrt{2}\cdot(-1)^{m+1}\mathrm{Im}(Y_k^{|m|}) & if\ 0 < m \le k \end{cases}$$

where $u_j$: series coefficient; $P_{lj}(0)$: Legendre polynomial of degree $l$; $Y_j(\vartheta,\varphi)$: modified even, symmetric, real and orthogonal SH basis. Laplace-Beltrami regularization was used to enhance smoothness of the function[6].
ODFs were min-max normalized and scaled by the fractional anisotropy (FA)[4].

## Results

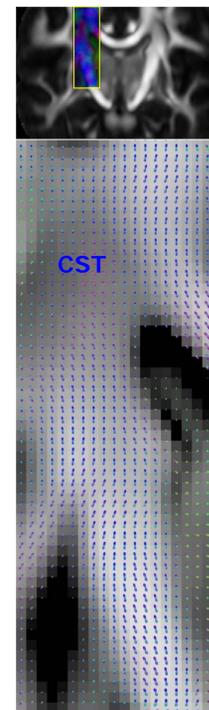The color shading of ODFs indicates orientation using the same three-color scheme as in DTI.



**Single orientation:** Figure 2 shows a resolved ODF map of the long corticospinal tract (CST). A map of the optic radiations (OR) containing single orientation fibers can be seen in Figure 3.
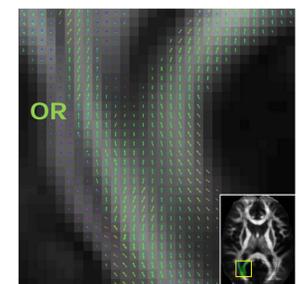


**Fig. 3.** ODF map of the optic radiations (OR)

**Multiple fiber directions:** Maps of computed ODFs in the frontal lobe of the brain can be seen on Figures 4,5. Figure 4 shows voxels containing both fibers of the corticospinal tract (CST) and the superior longitudinal fasciculus (SLF). Distinguished multiple fiber populations of the centrum semiovale (CS) and the superior longitudinal fasciculus (SLF) fibers can be seen in Figure 5.
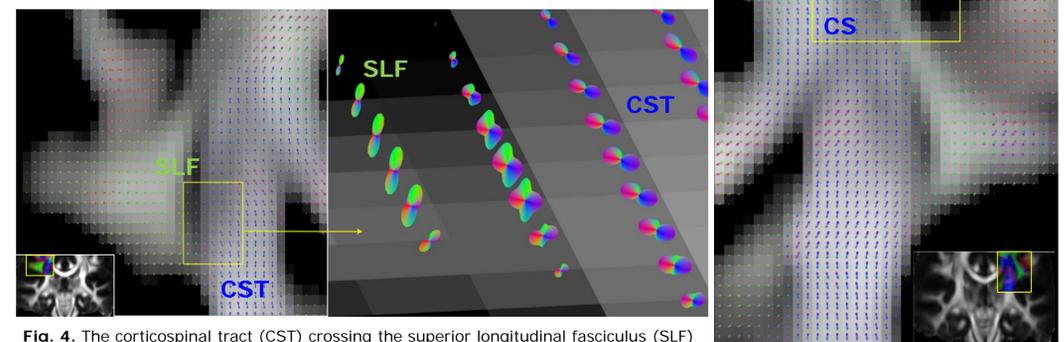


**Fig. 5.** The centrum semiovale (CS) crossing the superior longitudinal fasciculus (SLF)

**Fig. 2.** ODF map of the corticospinal tract (CST)



**Fig. 4.** The corticospinal tract (CST) crossing the superior longitudinal fasciculus (SLF)

## Discussion and conclusions

This work presents a HARDI template of the human brain. 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. The presented approach 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

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