Whole-Brain Tractography Incorporating ICA based Crossing-fiber Orientations

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Introduction

High angular resolution diffusion imaging (HARDI) [1] is commonly used to detecting multiple fibers within a voxel. HARDI however imposes a relatively long scan time as it commonly requires > 100 gradient directions, making it currently unsuitable for many clinical applications. The objective of this work was to investigate whether Independent Component Analysis (ICA) could be used to detect multiple fibers in routine clinical tractography where 1.5-3.0T systems are used with ~25 gradient directions to acquire data in 5-10 minutes. Simulation and experimental studies are presented in this paper suggesting the suitability of ICA to detect 2-3 fibers per voxel. Whole-brain tractography incorporating multiple fibers per voxel is then conducted to show recovery of tracts missing in conventional single-fiber streamline tractography due to (most likely) the fiber-crossing problem.

Method

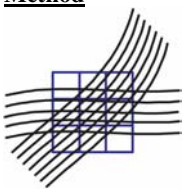

Fig. 1a

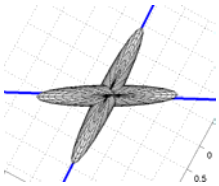

Fig. 1b

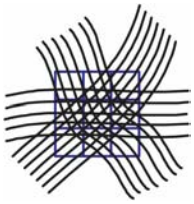

Fig. 1c

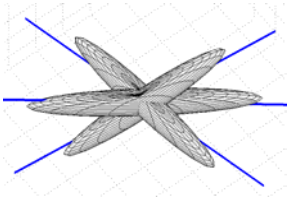

Fig. 1d

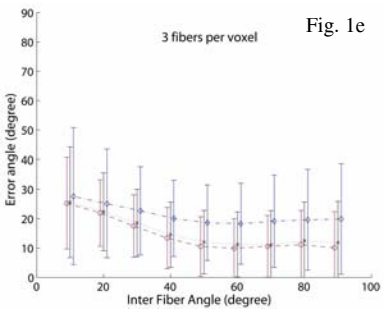

Fig. 1e

ICA requires that individual sources, where a source in the ICA framework means a 25-element diffusion weighted MRI vector (for 25 gradient directions), be statistically independent and non-Gaussian. Assuming diffusion around one fiber does not affect significantly the diffusion around another fiber, sources could be thought of as being independent. Non-Gaussianity of sources was established experimentally from a bootstrapping statistical analysis of the probability density function of corpus callosum (splenium and genu) voxels, most likely to contain a single fiber per voxel (i.e., single sources), which shows negentropy=2.2419 (0 for Gaussian) and kurtosis =-0.8824 (0 for Gaussian). A mixture-of-tensors model was used to simulate DTI data under the assumption that fibers cross over a small neighborhood with different mixing ratio among neighbors (See examples in **Figs. 1a** and **1c**). Quantitative recovery of the angle between fibers was estimated by a Monte Carlo simulation for a mixture of randomly oriented tensors with a ten-neighbor configuration. Two or three fibers were oriented at random angles in three-dimensions and ICA was applied to detect the individual fibers after adding random complex noise to the data. The results of the simulation study to recover two or three crossing fibers are shown in **Figs. 1b** and **1d**, suggesting good recovery of the orientation or eigen-vectors of individual tensors, as shown by the blue lines across the original tensors shown as crossing ellipsoids. The eigen-values, i.e., the shape of the tensors were not recoverable by ICA. The recovery error as a function of the inter-fiber angle is plotted in **Fig. 1e** for three tensors, suggesting a recovery accuracy of ~20 degrees. Better recovery was obtained for two fibers with an error of ~15 degrees.

Whole-brain human DTI studies were conducted at 3T and 1.5T using 4mm thick 28-slice EPI acquisition with 25 gradients directions for a total data acquisition time of 7min 53s. The estimation of number of fibers per voxel (which is required for ICA) was conducted by a K-means segmentation procedure applied to clustered maps of: SPM2 determined white matter (WM) probability map using T1 images co-registered to the b0 images, linear anisotropy (CL), fractional anisotropy (FA) and trace of the single tensor. The top half of the CL clusters were classified as single fiber per voxel, the top half of the FA clusters in remaining voxels as two fibers per voxel, the top half WM clusters in remaining voxels as three-fibers per voxel, the top half of the 'trace' clusters in the remaining voxels as CSF and all remaining voxels were classified as gray matter. Whole-brain tractography was conducted by a standard PCA based streamline approach using tensor interpolation at a step size of 0.2mm, and compared to ICA tractography with same step size but vector interpolation. ICA tractography was initiated for each fiber separately in voxels containing multiple fibers. When a voxel with multiple orientations was encountered along the path, the orientation indicating minimum deflection was selected [2]. Tracts were sorted from ICA and PCA whole-brain tractographies to compare their performance.

Results and Discussion

A sample slice of the color-coded ICA estimated orientations of two or three fibers and PCA estimated orientation of single fiber overlaid on FA is presented in **Fig. 2**. The sorted fronto-occipital and thalamo-frontal tracts using identical ROIs are presented in **Figs. 3a-d**. Note that tracts traversing known fiber-crossing regions in the prefrontal brain areas maintain better continuity through these regions with ICA than PCA (see arrows), revealing many tracts with ICA that are undetected in PCA due to likely termination or misdirection (incorrect orientation) in crossing regions.

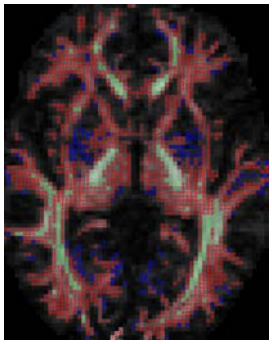

Fig. 2: (red) two fibers, (blue) three, (green) one.

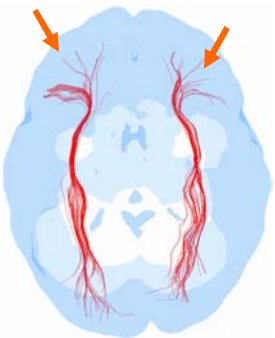

Fig. 3a: Fronto-occipital ICA

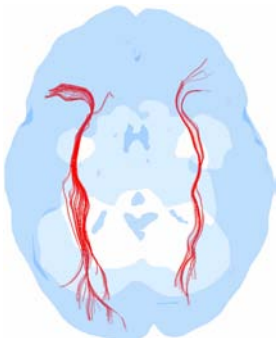

Fig. 3b: Fronto-occipital PCA

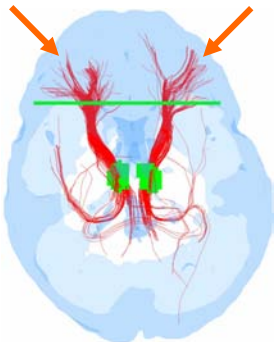

Fig. 3c: Thalamo-frontal ICA

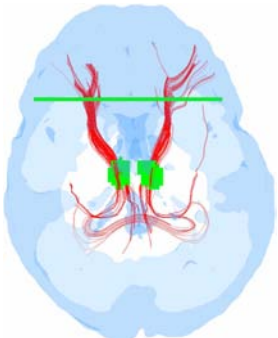

Fig. 3d: Thalamo-frontal PCA

[1] DS Tuch, Magn. Res. Med., 52: 1358-1372, 2004. **[2]** GJM Parker and DC Alexander, Phil. Trans. R. Soc. B 360: 893-902, 2005.