Validating the Tensor Distribution Function for Fiber Reconstruction in HARDI (High-Angular Resolution Diffusion Imaging)

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Introduction: Diffusion tensor imaging (DTI) reveals white matter microstructure and fiber pathways in the living brain by examining the 3D diffusion profile of water molecules in brain tissue. Even so, DTI-derived measures will be incorrect where fibers cross or mix, as the single tensor model cannot resolve these more complicated white matter configurations. High-angular resolution diffusion imaging (HARDI) addresses this problem by applying more than 6 independent diffusion-sensitized gradients. Many HARDI reconstruction methods (e.g., *q*-ball imaging, DOT, PAS) impose restrictive assumptions on fibers, e.g., all fiber tracts must have the same anisotropy profile. Here we model the HARDI signal more flexibly, as in [1], as a unit-mass probability density on the 6D manifold of symmetric positive definite tensors, yielding a Tensor Distribution Function (TDF), or continuous mixture of tensors, at each point in the brain. The TDF can model fiber crossing and non-Gaussian diffusion. From the TDF, one can derive analytic formulae for the water displacement probability function, orientation distribution function (ODF), tensor orientation distribution function (TOD), and their corresponding anisotropy measures. Here we further develop the TDF framework, verifying its accuracy in revealing fiber crossings in human brain HARDI data.

Methods: We modeled fiber crossings in each voxel as a mixture of tensors with arbitrary shapes, using one tensor for each component fiber. All fiber tracts were assumed to be cylindrical, by forcing two eigenvalues (out of three) to be equal for each individual tensor in the solution space D. Thus, each tensor was represented by two scalars (specifying 3 eigenvalues) and one direction (unit vector). To implement the TDF framework, the unit sphere was initially parameterized using the n diffusion-sensitized gradient directions $\mathbf{q_i}$. This allows discrete sampling of the corresponding TOD and straightforward determination of dominant fiber directions by thresholding. We used a multi-resolution strategy to optimize computational efficiency and precision. At each resolution, new unit directions were included locally on the unit sphere around the maximal values of the TOD. This increases angular resolution without sacrificing computational speed by adaptively upsampling regions on the unit sphere where dominant fiber directions are located. New directions were selected from icosahedron-based triangulations approximating the unit sphere (up to the 7^{th} order tessellation with n=642 directions).

Results: ODFs calculated by using the TDF framework correctly recovered known fiber crossings of cortico-cortical U-fibers and *longitudinal fasciculi* in 94-direction human brain HARDI data (4 Tesla; 1.8x1.8x2mm voxels; b=1159s/mm^2; **Figure 1**). Inset panels (c)-(e) show callosal genu fibers interspersed with frontal association fibers (c), mixed corticothalamic and longitudinal fibers (d), and the correct recovery of single-tensor diffusion patterns in the corpus callosum (e).

Conclusions: The tensor distribution function is a novel signal reconstruction method that can resolve intravoxel fiber crossing in HARDI. As a density on the underlying tensors, the resulting tensor orientation density (TOD) has sharp maxima at dominant fiber crossings, and the standard ODF representation can be readily derived from it.

References: [1]. Leow AD et al. *The Tensor Distribution Function*, Magnetic Resonance in Medicine 2008, in press.

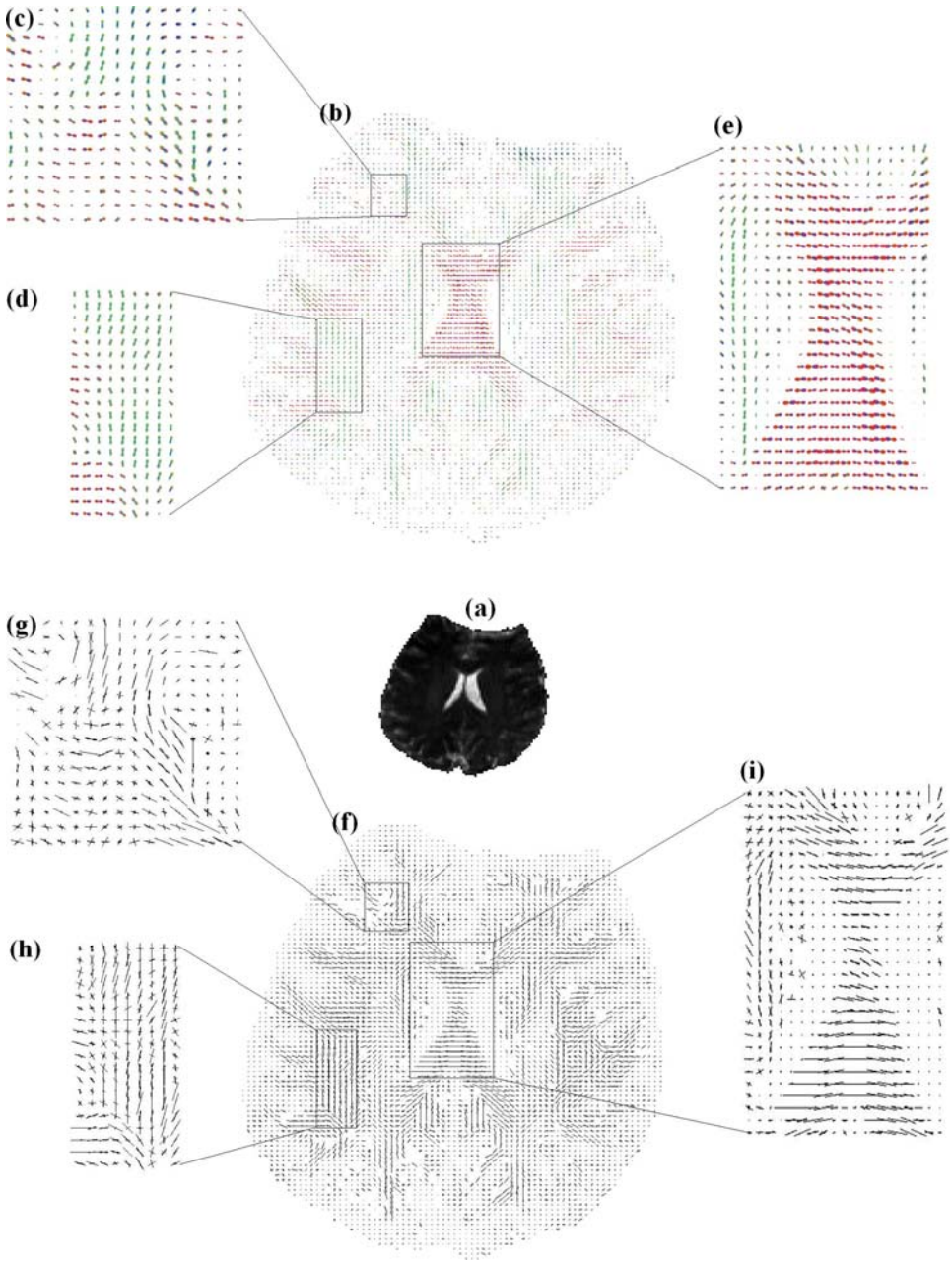

Figure 1. (a) T2-weighted image; (b) Orientation Density Functions (top) and Tensor Orientation Density Functions (bottom) computed from 105-gradient HARDI data; (c),(g) fibers in the callosal *genu* mixing with frontal association fibers; (d),(h) mixed corticothalamic and longitudinal fibers; and (e),(i) correct single-tensor recovery in the corpus callosum.