Effect of Order and Sharpening on Orientation Distribution Function for Identifying Fiber Orientations in Higher Order Tensor Model

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Introduction: High angular resolution diffusion imaging (HARDI) was introduced to resolve crossing, branching, and kissing fibers [1]. Different modalities and estimation methods for analyzing the HARDI data have been proposed to overcome the limitations of single tensor DTI. One such method is the apparent diffusion coefficient (ADC) profile using high-order tensors (HOT) [2-5]. By combining the high-order tensor formulation with spherical deconvolution technique a positive-definite orientation diffusion function (ODF); denoted as Cartesian Tensor-ODF is estimated [6]. The maxima of ODF correspond to the fiber orientation for fiber tracking. The spherical deconvolution method sharpens the ODF and helps to identify fiber orientations in complex fiber structures, especially when their crossing angles are acute. The basic assumption in spherical deconvolution method is that the estimated diffusion ODF is formed by convolution between the single fiber diffusion ODF kernel, and the true fiber orientation distribution (FOD) [7]. Using the Funk-Hecke theorem, a linear relationship between the spherical coefficients of the unsharpened and sharpened ODFs exists [8]. In this study we analyzed the effects of tensor order and the order of spherical harmonics (denoted by l) for the selection of ODF peaks (fiber orientations) and reconstruction of branching fiber bundles. We demonstrated, as an example, the tracts reconstructed from the seed region at the mid body of corpus callosum (CC) using 4th and 6th order tensor models which are deconvolved with ODF kernel of a single fiber represented by 4^{th} and 6^{th} order spherical harmonic basis functions.

Materials and Methods: Diffusion weighted images were acquired on a Philips 3T scanner on five normal controls. A 32-chanel head coil with a SENSE factor of 2 was used for data acquisition. Multi-slice, diffusion-weighted images were acquired using a single shot spin echo EPI sequence with 81 diffusion encodings. The sequence parameters were: FOV= 256x256 mm2, slice thickness = 3mm, TR/TE = 8235/72 ms, b-value = 1600 s/mm^2. Using HARDI data, ODF was calculated, from which the principal diffusion directions (PDD) were extracted [5, 6]. The modified method based on local variation and clustering methods as described in [9] was used to select principal diffusion directions. This procedure picks the peaks where the local maximum method fails. The fiber bundles from the mid body of CC and from the centum semiovale region were reconstructed using our fiber tracking procedure described in [10] to compare fiber pathways of branching fibers.

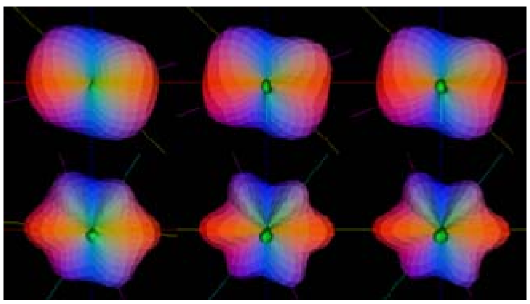

Fig. 1: First Row: Fourth Order Tensor, Second Row: Sixth Order Tensor. First column: unsharpened, second column sharpened with l = 6, third column sharpened with l = 8.

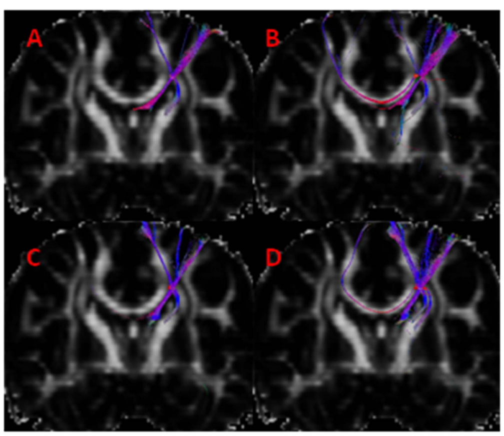

Fig.2: Fiber pathways generated from the seed region in the centrum semiovale (2x5x2). Fourth order tensor (A and B); Sixth order tensor (C and D); unsharpened (A and C); sharpened and modified (B and D)

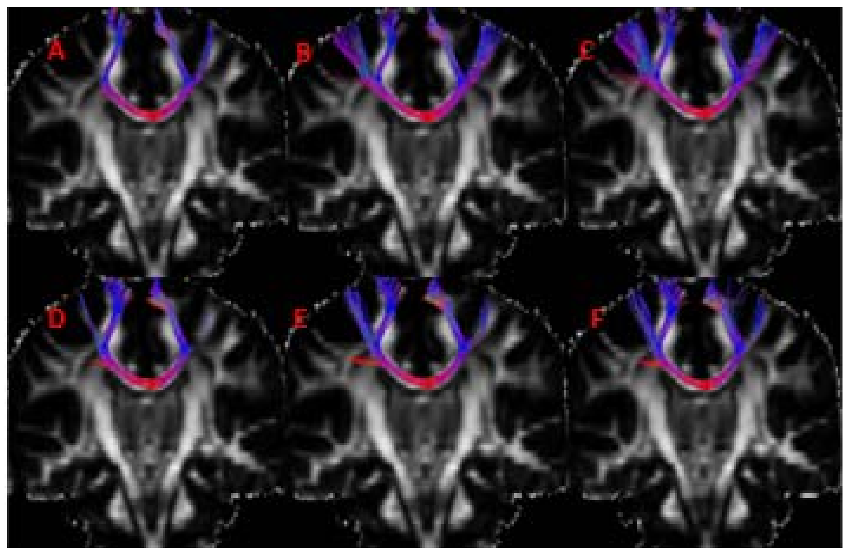

Fig. 3: Tracts generated by placing the seed from the mid body of the CC. Fourth order tensor (A-C) and (D-F) represent sixth order tensor. (A and E): unsharpened ODF, (B and E): sharpened ODF; (C and F): Sharpened and Modified ODF.

Results: The ODFs in a voxel in the centrum semiovale is shown in Fig. 1 for 4th and 6th order HOT deconvolved with spherical basis functions of order 4 and 6. Multiple crossing fibers are known to be present in this region. As can be seen from Fig. 1, the 4^{th} order tensor shows two peaks without deconvolution. Deconvolution with l= 4 and 6 improved the sharpness of the peaks, but still only three peaks are detectable. In contrast, the 6^{th} order tensor shows four peaks. Deconvolution improved the sharpness of the peaks. Deconvolution based on l = 4 and 6 provided similar results. Figure 2 shows tractography derived from HOT of orders 4 and 6 along with deconvolution with l= 4 and 6, with the seed voxel placed in the centrum semiovale. It can be seen from this figure that 6^{th} order HOT with l=6 reproduced the known fibers in this region. Consistent with the ODF results, HOT of order 4 performed poorly. Figure 3 shows the tracts derived using the 4^{th} and 6^{th} order HOT with the seed placed in the body of the CC. The tract in Fig.3 (A and D) shows that the unsharpened ODF was unable to reconstruct the branching fibers. From Fig.3 (B and E) one can observe that the sharpening method has reconstructed significantly more branching pathways than the unsharpened method. The sharpened and modified method has reconstructed more fiber pathways than unsharpened and sharpened methods as it can be seen from Fig.3 (C and F). No significant differences were observed between fiber pathways reconstructed with HOT of order 4 and 6 in regions with single principal diffusion direction.

Discussion: These results show that at least sixth order tensor is needed to reconstruct crossing and branching fibers. These results also demonstrate that deconvolution helps improve the tractography, especially when the fibers cross at acute angles. We did not observe any improvement by using larger than six basis functions. Finally, because of the limited number of diffusion directions (81), we did not pursue analysis with HOT beyond order 6.

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