Multi-directional anisotropy obtained from the diffusion propagator

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Introduction: Diffusional anisotropy is a key parameter of interest in the study of brain disorders. In conventional diffusion tensor imaging (DTI) [1], fractional anisotropy (FA) [2] measures the extent of diffusivity along the principal direction relative to the perpendicular directions, yielding a gauge of axonal integrity. However, DTI-FA assumes a single diffusion tensor, and hence does not adequately describe the general case of multiple components and directionalities, as seen in voxels with crossing-fibers, partial-volume effects and in gray matter.

Methods: As compared to a single diffusion tensor (Fig. 1a), the number of directions in a crossing-fiber maybe inferred from the number of peaks in the orientation distribution function (ODF, or Ψ), but requires knowledge of the diffusion propagator (Fig. 1b), which can be determined using diffusion spectrum imaging (DSI) [3]. In addition, the ratio between the minimal and maximal values from an ODF may be an indication of multi-fiber diffusional anisotropy. An ODF-based multi-directional anisotropy (MDA) metric is proposed, defined as $\mathrm{MDA} = (1-\mu)/\sqrt{1+2\mu^2}$, where $\mu = \left(\min_i \Psi_i / \max_i \Psi_i\right)^{2/3}$. It can be shown that MDA is analytically equivalent to FA if (i) a single diffusion tensor and (ii) equal perpendicular diffusivities (D_2=D_3) are assumed.

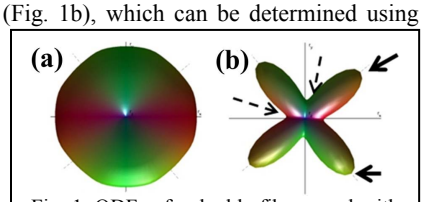

Fig. 1. ODFs of a double-fiber voxel with perpendicular directions, obtained with (a) single diffusion tensor, and (b) diffusion propagator (arrows indicate peaks along and troughs between simulated directions).

The diffusion propagator was determined using DSI acquisition. Compressed-sensing was applied for four-fold acceleration [4] in 11^3 q-space with 127 diffusion samples. The ODFs were computed using projections taken at 5° angle intervals. For *in vivo* imaging, normal subjects were imaged at 3T (GE, MR750) with an 8-channel phased-array coil (128×96×18 slices, sagittal plane, TR/TE = 3000/118 msec, ASSET R = 2, b_{max}=10,000 sec/mm^2).

Results: The results of Fig. 2 suggest that plots of both FA and MDA were proportional to simulated FA when a single-fiber was simulated. When two fibers of equal anisotropy and diffusivity were simulated (Fig. 3), DTI-based FA provided a bi-modal distribution of FA. Increasing the DTI directions from 25 to 127 reduced FA variance in a single-fiber, but not in a double-fiber case. In the double-fiber case, as compared to DTI-FA, the mean MDA was higher while the variation of MDA was reduced. The distribution of MDA was clustered by the fiber direction count (N), with bi-modal behavior observed primarily when N = 1 was detected.

In vivo (Fig. 4), the N = 1 regions coincided well with high DTI-FA regions such as the corpus callosum, where the MDA values were lower than FA. In N = 2 and 3 regions, notably in the gray matter and cerebellum, MDA was higher than FA.

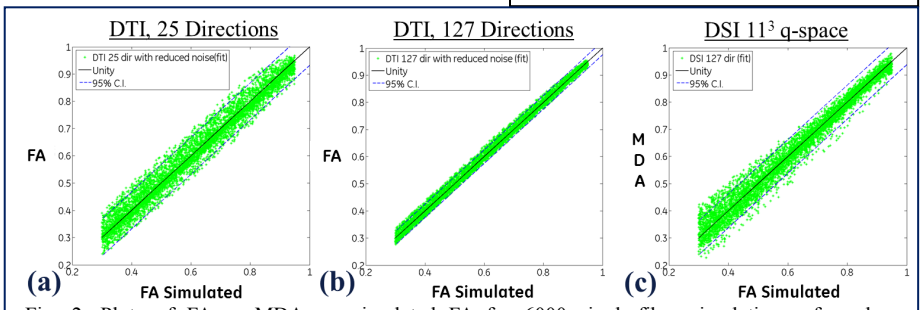

Fig. 2. Plots of FA or MDA vs. simulated FA for 6000 single-fiber simulations of random directionalities for (a-b) DTI (noise=3.6%) and (c) DSI (noise = 5%), demonstrating linearity of assumed FA vs. calculated FA and MDA.

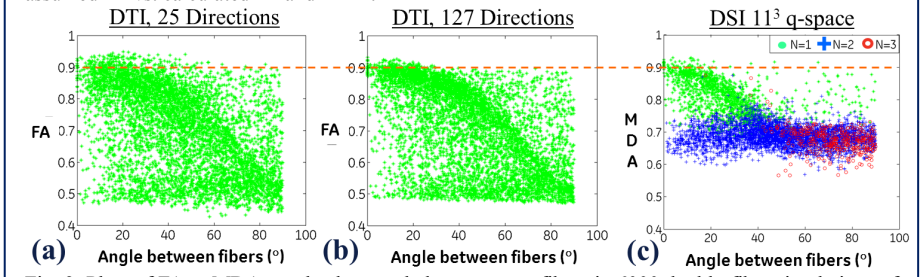

Fig. 3. Plots of FA or MDA vs. absolute angle between two fibers in 6000 double-fiber simulations of equal diffusivity (simulated individual FA = 0.9 shown by red line) for (a-b) DTI and (c) DSI that also show clustering of MDA with fiber direction count (N).

Discussion and Conclusion: The novel MDA metric is shown to be equivalent to FA in single-fiber voxels, but is superior to FA in double-fiber voxels. The lower SNR associated with longer TEs in DSI may result in reduced MDA in highly anisotropic regions (FA > 0.8). While ODF-based generalized FA had also been proposed [5], a correlation between MDA and FA is now shown. CS-acceleration of DSI should allow fiber direction count and MDA to be obtained in a clinical setting for multi-parametric analysis of anisotropy in crossing-fiber and gray matter regions.

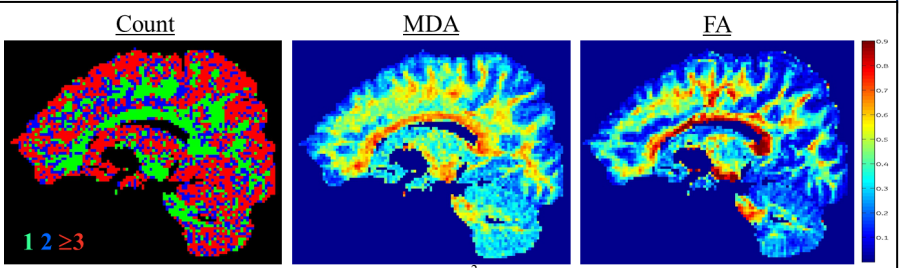

Fig. 4. Sagittal DSI acquisition (b_{max} = 10,000 sec/mm^2, TE = 118 msec) provides both fiber direction count and MDA, as compared to FA provided by DTI acquisition (b = 2000 sec/mm^2, TE = 94 msec).

References: [1] Basser, Biophys J 66, 1994; [2] Pierpaoli, Magn Reson Med 36, 1996; [3] Wedeen, Magn Reson Med 54, 2005; [4] Menzel, Magn Reson Med 66, 2011; [5] Tuch, Magn Reson Med 52, 2004.