On the Behavior of DTI and Q-ball Derived Anisotropy Indices

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Purpose:

In a typical diffusion imaging acquisition of the human brain, more than one third of the voxels contain heterogeneous fiber configurations. However, the behavior of diffusion anisotropy indices (DAI) in diffusion tensor imaging (DTI) and q-ball imaging (QBI) has never been systematically analyzed under these conditions. With the exception of [1], who evaluate the dependency of the generalized fractional anisotropy (GFA) on the number of acquired gradient directions, current QBI indices have so far not been evaluated with respect to accuracy, precision, stability under different acquisition parameters and contrast-to-noise ratio (CNR) [2,3]. This applies for the original q-ball reconstruction scheme [4] as well as for the recently proposed scheme with solid angle consideration referred to as QBI* [5]. The success of current high angular resolution diffusion imaging (HARDI) techniques is directly linked to their clinical applicability, and this applicability is directly linked to two central questions: (1) What are the advantages and drawbacks of quantification using QBI with its corresponding HARDI acquisition scheme, and (2) how do established and current indices behave under different conditions of intra-voxel orientational heterogeneity (IVOH). To investigate on this, a systematic analysis of DAIs with respect to noise, acquisition settings and fiber configuration was performed using simulations and measurements on crossing fiber phantoms.

Methods:

Four novel fiber crossing phantoms (45° and 90°, interleaved and stacked winding) with realistic bundle sizes and high FA values that match in-vivo conditions were constructed by winding fifteen micrometer polyester fibers around spherical polyamide spindles [6]. MR images were acquired on a 3.0 T MR scanner (Magnetom Trio, Siemens), twice refocused spin echo EPI sequence, in plane resolution=2×2 mm², 3-7 mm slice thickness, diffusion weighting strength b_1=3500 s/mm² and b_2=1000 s/mm², 252 diffusion directions, TE=123 ms, TR=3.4 s, bandwidth=2300 Hz/Px. Additionally, Monte Carlo simulations were performed to simulate MR-measurements for 162 gradient directions and different fiber configurations (0°/single fiber, 30°, 45°, 60° and 90° crossings). Diffusion tensors were computed by linearly fitting a least squares solution. QBI reconstruction with regularization weight $\lambda=0.06$ and $\ell=8$ [4] and QBI* reconstruction [5] were performed. 1002 spherically distributed directions were sampled from the ODF. dDAI/dFA is the derivative of the DAI with respect to underlying true FA and was calculated as a measure of contrast [2].

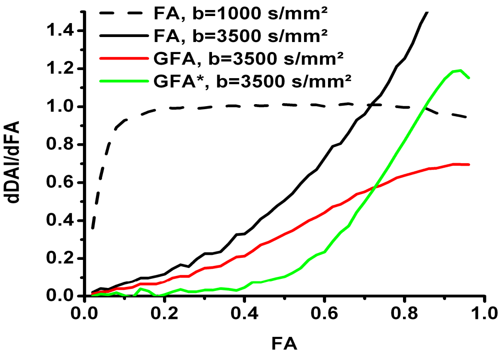

Fig. 1: Simulated contrast values of DAIs in single fibers at different underlying true FA (SNR 20:1)

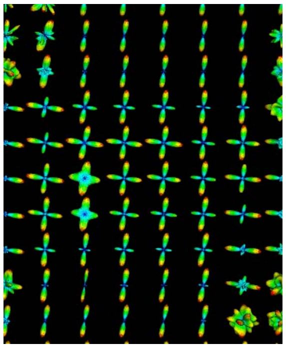

Fig. 2: QBI*-ODFs in the 90° phantom fiber crossing

Results:

Compared to the FA at b = 1000 s/mm², all indices showed reduced contrast at b = 3500 s/mm² (Fig. 1). While the FA performed best with regard to contrast, its precision was the lowest in both single and crossing fiber configurations (Fig. 3). GFA* exhibited the best accuracy values at different SNR (Fig. 4). All measures showed a clear b-value dependency (Fig. 5). GFA* was most stable against b-value variation. The results were supported by phantom experiments (Fig. 2), where deviations up to 22.3% (FA) and 53.4% (GFA) where measured when doubling SNR. With maximal 6% deviation, GFA* remained stable at different levels of SNR and different crossing situations. Further phantom experiments revealed a relative change of -20.2% (FA), 104.0% (GFA) and 6.0% (GFA*) in a 90° crossing and -14.3% (FA), 68.5% (GFA) and 1.2% (GFA*) in a 45° crossing from one acquisition at b = 1000 s/mm² to another one at b = 3500 s/mm². Experiments were performed in order to further assess the behavior of the indices under different conditions of IVOH. The relative deviations of anisotropy in a simulated single fiber voxel of FA = 0.7 compared to a 90° crossing voxel of two bundles at FA = 0.7 that equally share the voxel volume were 62.3% (FA), 43.2% (GFA) and 10.8% (GFA*). In phantom experiments, we measured deviations of 34.3% (FA), 35.5% (GFA) and 8.67% (GFA*) in a similar setup under real noise conditions. Simulated CNR at SNR = 20:1 and FA = 0.7 were 32.9 (FA), 38.4 (GFA) and 19.6 (GFA*) [2].

Discussion: GFA* showed the lowest dependency on b-value and had the best results regarding accuracy and precision at b = 3500 s/mm². The index also performed well in crossing regions, since its values best resembled the mean anisotropy of the fibers sharing a voxel and thus is a better measure of underlying tissue integrity. Main drawback of the GFA* was its low CNR, especially in single fibers with low anisotropy.

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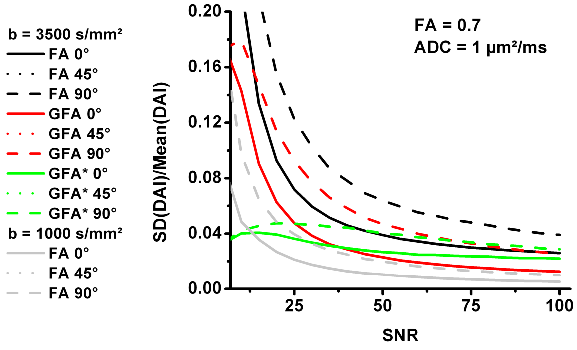

Fig. 3 Simulated standard deviation values as function of SNR (precision)

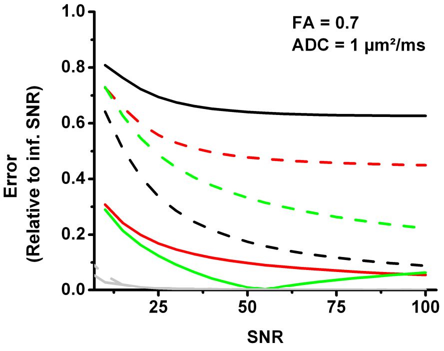

Fig. 4 Simulated relative error values as function of SNR (accuracy)

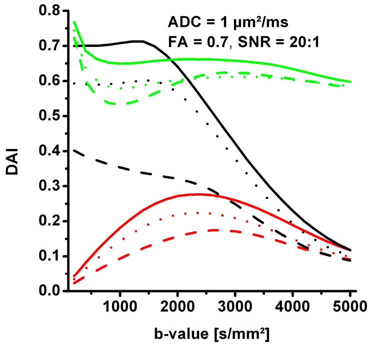

Fig. 5 Simulated DAI values as function of the applied b-value