Analysis of the generalized fractional anisotropy in regions of fiber crossings: a simulation study

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PURPOSE: Quantitative tractography methods which are currently in development in several groups require a detailed understanding of the diffusion contrast mechanisms in order to better characterize tissue properties specific to each white matter (WM) fiber tract. In this framework, this study aims at using Monte-Carlo simulations to understand how the generalized fractional anisotropy (GFA) is affected in the case of variable configurations of WM fiber tracts crossings. In particular, a linear sum of specific anisotropy measures for each of the tracts (linGFA) is compared to the usual GFA and simulations are used to assess the effects of varying partial volume, crossing angle and anisotropy of each compartment. Additionally, we use this approach with different ODF reconstruction schemes to study how our analysis generalizes to these methods.

METHODS: Data simulation: Monte Carlo simulations are performed in Matlab. MR signals are simulated according to a bi-tensor model with Rician noise and SNR of 20 ([1], [2]). Fractional anisotropies (FA1, FA2) of the two tracts are varied from 0.33 up to 0.71. Tensors are cylindrical with constant trace of $3.0\text{x}10^{-3}\text{mm}^2/\text{s}$. The proportion of the first tract (F1) is varied in the range [0.15, 0.95] and the angle (α) between the two tracts is of π/6, π/3 or π/2. Also the ODF is estimated using three different reconstruction schemes (M_odf): QBI [3], exact QBI (EQBI)[2] or DSI[4]. Codes for the ODF estimation algorithms are based on [5]. For every specific configuration (FA1, FA2, F1, α, M_odf) 250 different datasets are created and estimated in order to guarantee stability of the results.
Generalized Fraction anisotropy (GFA): GFA is a generalization of the concept of fractional anisotropy for HARDI methods and is computed as $GFA = \frac{std(\Psi)}{rms(\Psi)}$, where Ψ is the ODF function [3]. In the case of the multitensor model of diffusion the theoretical exact ODF can be expressed as $refODF(r) = \frac{1}{Z}(\pi t)^{\frac{1}{2}} \sum_i^M f_i \left(r^T D^{(i)-1} r\right)^{-\frac{1}{2}}$, where r is the unit orientation, t the total diffusion time, Z a normalization constant, f_i the partial volume of tract i and $D^{(i)}$ its tensor [2]. The reference GFA (refGFA) is then computed using the theoretical refODF. In addition, reference GFAs are computed for each of the tract and the weighted sum $\text{linGFA} = \sum_i^M f_i GFA_i$ is used to estimate the reduction in the case of fiber crossings compared to the value expected if GFA of crossing tracts would add linearly.
Real data: data of a single subject were acquired on a Trio Siemens 3T scanner with 32-channel head coil and a q4half DSI sequence. The ODF was estimated as in [4] and the number of fiber tracts, their proportion and direction were estimated from the ODF. Then, linGFA in each voxel was computed by fitting the refGFA formula to the estimated ODF with a conditioned non-linear least square method. The real dataset was used to highlight regions in which linGFA will provide better information for the tissue characterization.

RESULTS:

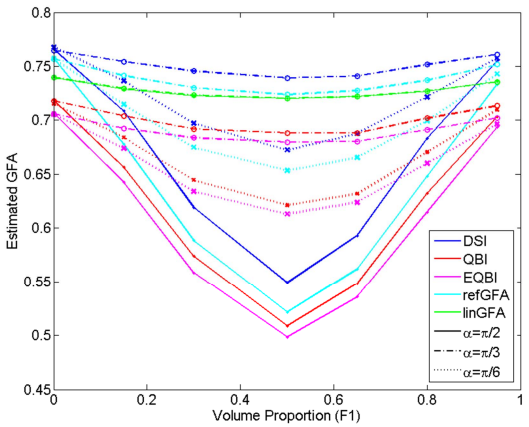

Figure 1: GFA estimation dependency on the F1. Colors represent different methods of estimation (see legend). Fixed parameters: FA1,FA2=0.71, Crossing angle is varied: α=π/2 (solid lines), α= π/3 (dotted lines) and α= π/6 (dash-dot lines).

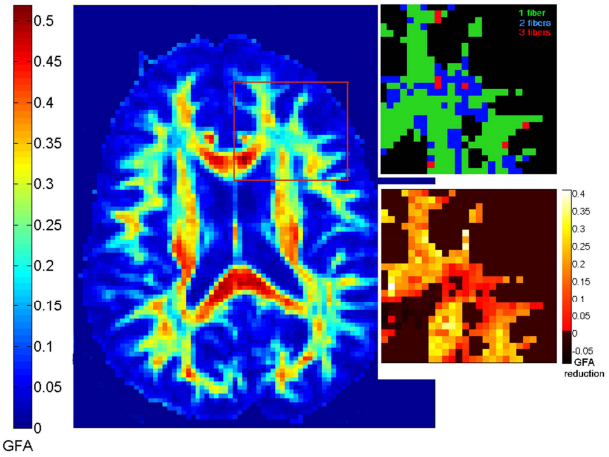

Figure 2: GFA map for the real dataset (Z=26). Squared boxes represent the number of fibers (top) and the difference linGFA-estimated GFA in the region marked by the red rectangle.

Results show that overall the standard GFA deviates from linGFA. The reduction in GFA is stronger when the angles between the fibers is close to π/2 and when the fibers have similar volume (Figure 1). When tracts have similar volume proportions, fibers with low anisotropy (FA2<0.4) have only little influence on the global GFA. These results do not depend on M_odf and also appear when the theoretical value refGFA is used. The effects of crossing angle α, anisotropies and volume proportion are similar for all methods, however overall DSI seems to be closer to refGFA. In Figure 2, regions of fiber crossings are highlighted and we see that using linGFA prevent reductions in anisotropy that is known to appear with standard GFA.

CONCLUSION: The aim of our analysis is to evaluate how the GFA deviates from a linear additive model (linGFA) in the case of fiber tracts crossings in a voxel. The analysis shows that the standard GFA depends on the crossing angle, the anisotropies of the crossing fibers and their respective volume proportions. However, the dependencies on these different characteristics of the fiber crossing configuration are not easy to interpret. Therefore, it is difficult to extract information specific to each of the fiber tracts from the standard GFA value. In opposition, linGFA has a linear relationship with the underlying characteristics of each of the fiber tracts and hence would be more for studies in quantitative tractography.

References: [1] Fritzsche K. et al, NeuroImage 51 (2010) [2] Canales-Rodriguez E,et al, Magn Reson in Med 61 (2009) [3] Tuch D., Magn Res in Med 52 (2004) [4] Wedeen V.J. et al, Magn Reson Med 54 (2005) [5] HARDI Tools http://neuroimagen.es/webs/hardi_tools/