Quantitative Assessment of Diffusional Kurtosis Anisotropy

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TARGET AUDIENCE

Diffusion magnetic resonance imaging (dMRI) is widely used for quantitative assessment of tissue microstructure for a variety of normal and pathological conditions. This study will benefit those who analyze diffusional anisotropy from dMRI data.

PURPOSE

Diffusion anisotropy measures are common for quantifying properties of tissue microstructure. Among them, fractional anisotropy (FA) is the most widely used.[1,2] However, FA has the shortcoming that it may take on small values, or in principle even vanish, despite the diffusion dynamics having significant angular dependence, for example, in white matter (WM) regions with multiple fiber bundle orientations.[2] For this reason, it may be of interest to consider additional measures of diffusional anisotropy. By estimating the kurtosis tensor, diffusional kurtosis imaging (DKI) accounts for higher order diffusion dynamics, when compared to diffusion tensor imaging (DTI). Consequently, it can describe more complex diffusion profiles. Here, for the first time, we compare several measures of diffusional anisotropy that incorporate information from the kurtosis tensor, including kurtosis fractional anisotropy (KFA) and generalized fractional anisotropy (GFA), to each other and to the diffusion-tensor derived FA.

METHODS

DKI datasets were acquired for 5 healthy volunteers ranging in age from 27 to 53 yrs, with a 3T TIM Trio MRI scanner (Siemens Medical, Erlangen, Germany) using a vendor-supplied diffusion sequence, 3 b-values of 0, 1000, and 2000 s/mm^2, and 60 isotropically distributed gradient directions to estimate the diffusion and kurtosis tensors. Acquisition parameters used were TR/TE = 7200/103 ms, voxel dimensions = 2.5 x 2.5 x 2.5 mm^3, matrix = 88 x 88, number of slices = 52, parallel imaging factor of 2, bandwidth = 1352 Hz/Px, and a 32 channel head coil with adaptive combine mode. For each subject, 3 full DKI datasets with a total of 25 images without diffusion weighting (b0 images) were acquired. Each independent DKI acquisition took 15.4 min, and the full DKI acquisition images took 48.9 min. To correct for subject motion, all b0 images for each subject were co-registered to the subject's first b0 image using SPM8 (Wellcome Trust Center for Neuroimaging, London, UK) with an affine, rigid body transformation with the normalized mutual information cost function. An average DKI dataset was then created by averaging all 25 independent b0 images and all 3 independent diffusion weighted images for each applied diffusion encoding gradient. FA was calculated with the conventional formula,[1] and the DKI approximation of the diffusion orientation distribution function (dODF) was calculated with the closed form solution provided by Jensen et al.[3] with a radial weighting power of $\alpha = 4$. GFA was calculated with the formula provided by Tuch,[4] and KFA was calculated with the formula provided by Hansen et al.[5] To estimate the number of fiber orientations from the DKI derived dODF, local maxima pair were identified using the quasi-Newton method.[3] To analyze anisotropy measures in different regions of interest (ROIs) across the 5 healthy volunteers, the FA maps from the average DKI datasets were normalized to the ICBM-DTI-81 FA white matter (WM) atlas[6] using SPM8 with non-linear transformation. The transformation for the average DKI dataset was then applied to all DKI-derived parameter maps from each of the independent DKI datasets. WM ROIs analyzed include the full WM ROI, corpus callosum (CC), cingulum bundle (CB), superior longitudinal fasciculus (SLF), and corona radiata (CR). Gray matter ROIs were also analyzed, including the lenticular nucleus (LN), which consists of the globus pallidus and the putamen of the basal ganglia, and the thalamus (Thal). To highlight differences between the anisotropy parameters, differential parameter maps were calculated as the difference between selected parameters of interest. To emphasize the average group difference in the anisotropy parameters, differential maps were generated from the mean of the normalized parameters.

Table 1. Mean Parameter Values within each ROI

	WM	CC	CB	CR	SLF	Thal	LN
FA	0.412(0.131)	0.494(0.144)	0.313(0.100)	0.390(0.087)	0.377(0.093)	0.274(0.054)	0.200(0.086)
GFA	0.539(0.151)	0.626(0.156)	0.446(0.140)	0.527(0.101)	0.517(0.124)	0.366(0.070)	0.275(0.108)
KFA	0.439(0.115)	0.469(0.124)	0.466(0.121)	0.441(0.072)	0.455(0.115)	0.338(0.048)	0.365(0.072)
XN	1.325(0.337)	1.242(0.290)	1.622(0.239)	1.485(0.407)	1.658(0.330)	1.343(0.245)	1.561(0.337)

Values represent the mean (± standard deviation) for the anisotropy measures in each ROI pooled from the average scans of all 5 subjects after normalization to the ICBM WM template.

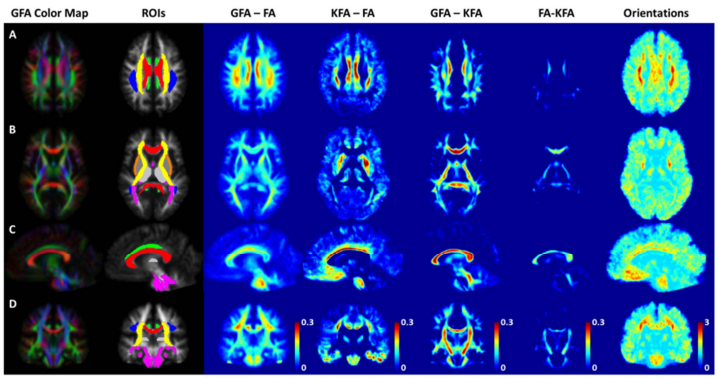

Fig. 5. Differential anisotropy maps for representative transverse (A) and (B), sagittal (C), and coronal (D) slices from the differential maps highlight differences in the anisotropy parameters. The first column illustrates the average of the normalized GFA colormaps.[4] The ROIs shown are CC (red), CB (green), SLF (blue), CR and IC (yellow), EC (orange), other WM structures (magenta), Thal (light gray), and LN (dark gray).

RESULTS

Mean parameter values are given in Table 1 and the differential anisotropy maps are given in Figure 1. In general, GFA is greater than FA throughout the WM, but the differences are enhanced in WM regions where multiple fiber bundle orientations are detected. Similarly, there is a strong correlation between regions enhanced in the KFA-FA differential map and regions with multiple fiber bundle orientations; however, KFA is also enhanced in deep brain structures such as the Thal and the LN. GFA and FA are elevated relative to KFA in regions with a single, well-defined, highly anisotropic fiber bundle orientation such as the CC.

DISCUSSION & CONCLUSIONS

FA can potentially take on small values despite significant diffusion anisotropy, due to the presence of complex fiber bundle geometries. As a consequence, alternative measures of diffusion anisotropy, such as the KFA and GFA, may be of interest. KFA is based purely on the kurtosis tensor and is mathematically distinct from the conventional FA measure. GFA, on the other hand, uses the dODF to quantify the degree of preferential diffusion mobility and thereby effectively integrates information from both the diffusion and kurtosis tensors. By measuring higher order diffusion anisotropy, KFA and GFA can help to better characterize more complex diffusion profiles and may be particularly useful for regions where WM fiber bundles cross.

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