Discovering white matter structure beyond fractional anisotropy maps

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Introduction

Anisotropy in the water diffusion MRI (dMRI) signal can be used to determine local white matter (WM) direction [1] and segment major pathways using tractography [e.g. 2, 3]. It has also been linked, in the form of fractional anisotropy (FA), to WM coherence and therefore, indirectly, to WM integrity [4]. It has been shown, however, that in partial volume (PV) voxels FA is underestimated compared with voxels containing only WM [5]. This can lead to an inaccurate estimation of either tract volume, i.e. discarding voxels containing WM, or coherence, i.e. including false FA values in the tract average. We address this problem by fitting a fully physically plausible, 2-compartment model to the dMRI data that correctly describes PV effects using local diffusion information.

Methods

We assume that each voxel may contain two tissue types, WM (anisotropic compartment) and either CSF or grey matter (isotropic compartment). The forward diffusion model is therefore described by a two-tensor equation, where we constrain one of the tensors to be prolate (cylindrically symmetric) and the other to be isotropic: $S_i = S_0 \left((1-v)e^{-bd} + ve^{-bd_\perp} e^{-bd_\Delta \cos^2 \gamma_i} \right)$

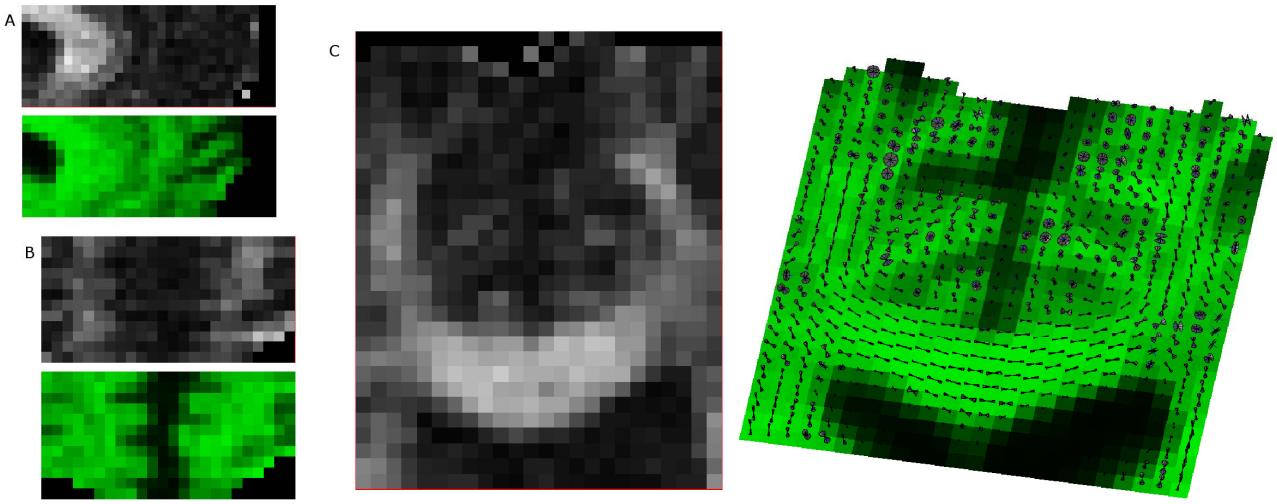
S_i denotes the signal measured for the i^{th} gradient direction, S_0 the signal without diffusion weighting, v the WM volume fraction, d the isotropic diffusivity, $d_\perp$ and d_Δ the anisotropic diffusivities such that $\lambda_1 = d_\perp + d_\Delta$ and $\lambda_2 = \lambda_3 = d_\perp$, and γ_i the angle between the diffusion gradient and estimated fibre directions. Additionally σ denotes the standard deviation of the noise, which we assume is Gaussian additive for simplicity. It is worth pointing out that both terms describe real physical compartments, unlike some other models [e.g. 3], and as a result v is a true volume fraction. The estimation of the parameters in the above model is difficult. We use custom Markov Chain Monte Carlo methods to reliably sample from the posterior distribution over the parameter space.

Data

Using a GE Signa 1.5T MRI scanner, a healthy 36 year old male volunteer underwent a whole brain dMRI exam (voxel dimension 2 × 2 × 2mm), based on single-shot spin-echo EPI, which consisted of 7 T_2- and 64 diffusion-weighted (b = 1000 s/mm^2) volumes. The dMRI data were then preprocessed to remove skull data and eddy current distortions using FSL tools (FMRIB, Oxford, UK), and maps of mean diffusivity (MD) and FA generated using DTIFIT.

Results

An ROI of 24 × 30 × 12 voxels containing the genu of corpus callosum was analyzed. Grey scale FA maps for saggital (A below), coronal (B) and axial (C) sections through this ROI were compared with the corresponding maps of the mean estimated WM volume fractions (in green scale where black = 0 and light green = 1). It is striking that the WM volume fraction maps capture more fine structure (particularly WM in the gyri) than is visible in the FA maps. Estimated water diffusivity constants (d, $d_\perp$ and d_Δ) agree with previous measurements. Estimated fibre directions (in C) agree with expectations as does the uncertainty of these estimates (indicated by grey cones equivalent to 95% confidence intervals), which is low in major WM pathwayhs and very high in crossing fibre regions and near cortical targets.



Discussion

The WM volume fraction maps can be used to estimate the volume of the pathways as well as providing better stopping criteria for tractography. Anisotropy computed for the fibre compartment can serve as a more precise (than FA) measure of tract integrity.

References

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