Estimating white matter tract volume in partial volume voxels with diffusion MRI

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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.

Theory

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: $S_i = (1-v)e^{-bd} + ve^{-bd_\perp}e^{-bd_\Delta \cos^2 \gamma_i}$. S_i denotes the signal attenuation for i^{th} gradient direction, 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 fiber 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 fitting of the above model is poorly posed on a single-voxel basis due to over-parameterization. In order to overcome this, we assume that the diffusivity parameters are locally constant when considering neighborhoods with one isotropic tissue type and one WM fiber present. We define regions-of-interest (ROIs) for which this assumption is taken to hold and estimate the parameters of the model jointly for each such region. Standard Markov Chain Monte Carlo methods are used to sample from the posterior distribution over the joint parameter space, where diffusivity parameters are shared across the ROI.

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 × 2 mm), 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 fractional anisotropy (FA) generated using DTIFIT.

Results

An ROI of 2 × 3 × 6 voxels containing WM, CSF and PV voxels was placed on the edge of the corpus callosum splenium (Fig. 1, left). The mean estimated WM volume fractions (plotted on the right of the Fig.1 in green scale where black = 0 and light green = 1) form consistent WM/CSF regions separated by a band of PV voxels, in visual agreement with FA/T_2-weighted maps. Estimated diffusivity constants are: d = 3 × 10^{-3} mm^{2}s^{-1} for the isotropic (CSF) compartment, $d_\perp$ = 0.4 × 10^{-3} mm^{2}s^{-1} and d_Δ = 1.2×10^{-3} mm^{2}s^{-1} for the WM compartment. These values agree with previous measurements. Estimated fiber directions (red bars) agree with expectations as does the uncertainty of these estimates (indicated by grey cones equivalent to 95% confidence intervals), which is low in WM and very high in CSF.

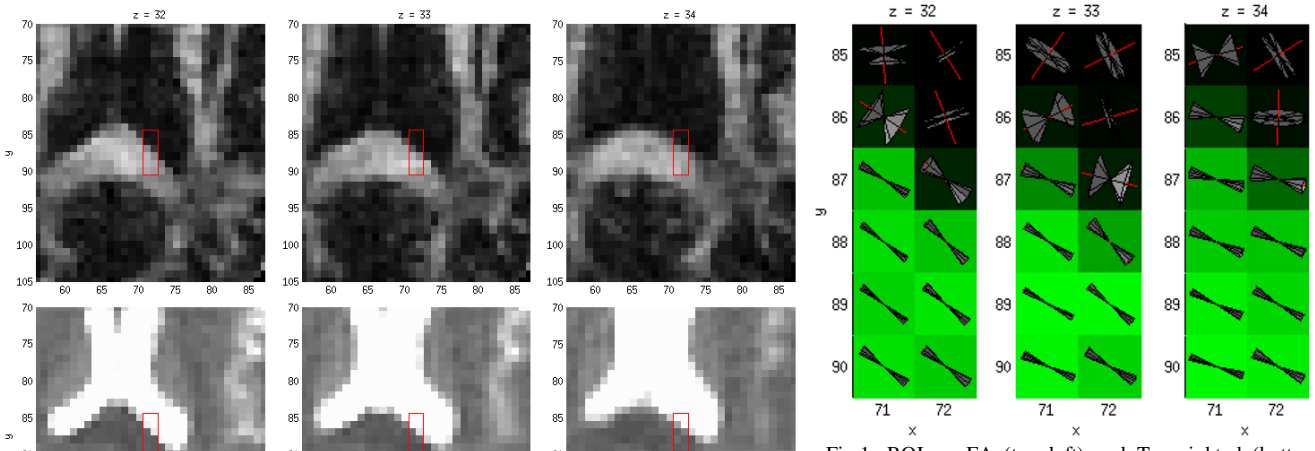

Fig.1: ROI on FA (top left) and T_2-weighted (bottom left) maps. On the right, the estimated fiber angles (represented by the cones of uncertainty) are overlaid on WM volume fractions (black = 0, light green = 1). Disk-like cones are expected for uniform distribution.

Discussion

The above results provide a proof of concept showing that the local sharing of the diffusivity parameters enables otherwise impossible estimation of WM volume in PV voxels. This method has the potential to improve tractography-based measures of tract volume and coherence for whole pathways by supplying more accurate structural information at the local level. While the current method is restricted to small ROIs for which constancy in local diffusion parameter values holds, we are currently developing a more advanced approach to modeling global variability while retaining local similarity.

References

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