NODDI with dispersion anisotropy

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PURPOSE This work presents a technique for estimating the dispersion anisotropy in neurite orientations, using Neurite Orientation Dispersion and Density Imaging (NODDI) [1]. NODDI is a diffusion MRI technique, recently developed to directly quantify the microstructural features (density and orientation dispersion) of neurites in vivo, in the human brain. The parameters it provides offer higher specificity and sensitivity than standard indices from Diffusion Tensor Imaging (DTI), as shown in the preliminary application to epilepsy [2], dementia [3] and brain development [4]. One limitation of the current implementation is that it models neurite orientation dispersion with the Watson distribution, which constrains the dispersion about the dominant orientation to be isotropic (Fig. 1). This can neither accurately represent nor fully characterise the anisotropic orientation dispersion associated with complex fibre configurations, such as fanning and bending fibres. The present work develops a new NODDI model that can quantify the degree of this anisotropy and estimate the primary dispersion orientation. These features are not only important for mapping brain connectivity [5] but are also potential markers for disease diagnosis and monitoring. Using simulated and in vivo brain data, we assess the accuracy and precision of estimating the dispersion anisotropy using the NODDI protocol [1] and quantify the potential bias of the current NODDI model in estimating tissue microstructure.

THEORY NODDI model: The diffusion MR signal is modelled as the sum of contributions from the tissue, broken down into intra- and extra-neurite components; and a non-tissue compartment accounting for the CSF contamination. CSF is modelled as an isotropic compartment, while the tissue compartments account for the dispersion in the orientations of neurites as described in [1]. Similar to [6-8], we use the Bingham distribution [9] to accommodate orientation distributions of fanning and bending neurites. Bingham Distribution: This parametric distribution is the spherical analogue of 2-D Gaussian distributions. It is given by the dominant orientation μ, the primary dispersion orientation μᵥ, and their respective concentration parameters κ₁ ≥ κ₂ ≥ 0, as shown in Fig. 1. The primary dispersion orientation is orthogonal to the dominant orientation, thus requires only one more angle to be determined. Together with κ₂, the two are the only extra parameters to estimate compared to the original model. Reducing the orientations sampled by the protocol, which uses the Watson distribution, a special case of Bingham distribution [10], to enable the visualisation of Bingham distributions in terms of the familiar 3-D rendering of diffusion tensors (Fig. 2). The primary and secondary eigenvectors of OT are precisely μᵥ and μᵥ, the corresponding eigenvalues, 1 ≥ 1 ≥ 1/3, are functions of κ₁ and κ₂ [10] and reflect the relative concentration of neurites along the dominant and the primary dispersion orientations respectively. (The tertiary eigenvalue is not independent and is equal to 1 − 1 − 1.) The narrow dynamic range of these parameters makes them easier to visualise than κ₁ and κ₂, which range between 0 and ∞. We define the dispersion anisotropy about μᵥ in terms of the planarity measure [11], which is equal to (1 − 1)/1: 0 for isotropic dispersion (the Watson distribution) and 1 for the maximum dispersion when 1 = 1 = 0.5.

EVALUATION Data: The dispersion parameter estimation is assessed with diffusion MRI data of one healthy volunteer, acquired on a 3T Philips scanner (Gmax = 60mT/m), using the 4-shell protocol as in [1], which includes the 2-shell NODDI protocol as a subset. The evaluation uses the estimates from the 4-shell protocol as the pseudo ground-truth. Synthetic data was additionally generated as in [1] to support the assessment with known ground-truth. Analysis: The NODDI Matlab toolbox is used for fitting the data. The estimated parameters for the proposed (top) and the original (bottom) NODDI model, even in the presence of significant dispersion anisotropy. Synthetic data shows that the bias becomes non-negligible only when dispersion anisotropy is close to 1. Protocol comparison: Fig. 3 demonstrates that the clinically feasible NODDI protocol, with 2 shells, is necessary and sufficient for estimating the parameters of the new NODDI model. Reducing the orientations sampled by the protocol can further reduce the scan time, without significantly affecting the accuracy of the estimates. Future work will investigate the reproducibility of the parameter estimates.

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