High Angular Resolution Diffusion Imaging (HARDI) – An Alternative Approach to DSI?

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Abstract: High angular diffusion-weighted imaging (HARDI) delivers - due to its increased directional acquisition on diffusivity properties - more detailed information on white matter structure than the standard diffusion tensor model. However, representation of the additional information is challenging. Additional detail on fibre directionality may be detected by comparison of dedicated anisotropy measures (relative anisotropy RAI, spherical diffusion variance SDI) and deviations from the tensor-like representation. We used the recently proposed spherical diffusion variance index, and also suggest projection 2D-plots as a simple means for rating of fibre complexity.

Introduction: Diffusion tensor imaging (DTI) [1, 2] has gained in importance in detecting fibre structure and white matter pathologies. DTI provides the main orientation of fibre bundles in colour-coded diffusion maps and often more clearly delineates changes of tissue characteristics or loss of diffusion anisotropy than it is shown with isotropic diffusion maps (ADC) or conventional T1- and T2-weighted MR imaging. However, DTI restricts itself to its primary diffusion direction represented by the principal eigenvalue and its associated eigenvector in an orthogonal system of eigenvalues and -vectors. Fibre crossings, non-Gaussian diffusion due to boundary restrictions and exchange processes will result in reduced anisotropy independent from its origin. Recently, more sophisticated approaches have been proposed with high angular resolution diffusion-weighted MRI [3] or even with diffusion spectrum imaging (DSI) with 600 and more DW gradient directions [4-6], and subvoxel structure has been shown at regions containing fibre crossings.
Using high angular resolution DW imaging (HARDI), we compare anisotropy measures derived from the standard tensor model and the more detailed directional information from multiple DW directions.

Materials and Methods: Preliminary volunteer data were obtained on a 1.5 T clinical scanner (Siemens Vision, EPI-capable). The HARDI sequence scheme consisted of a single-shot DW SE-EPI acquisition (TR/TE = 5000/137 ms, TH = 4 mm, FOV = 220x220 mm^2, MAT = 128x128) containing gradient lobes for DW (b = 0, 1500 s/mm^2) in 66 homogeneously arranged directions in space (tesselations of a tetrahedron). Amplitude images were averaged from 8 acquisitions; total acquisition time was 45 min. Eddy currents distortions were corrected and images were interpolated by cubic splines. 66 elements D_i obtained by a pixelwise exp. least-squares fit were combined to determine
1.) the tensor elements $D_{ij,\ (i,j=x,y,z)}$ by a multi-variate linear least-squares fit. After tensor diagonalization and calculating the 3 eigenvalues and -vectors, maps of the trace (ADC), the relative anisotropy index (RAI, normalized standard deviation of eigenvalues) and colour-coded DTI were estimated (Fig. 1 a, b).
2.) the spherical diffusion variance index (SDI) [3] as normalized standard deviation of all directional dependent diffusion coefficients, describing the variance from isotropic diffusion without using any additional model information (Fig. 1).

For a fair comparison between RAI (originally calculated from 3 values) and SDI (66 values), additional 63 values were theoretically estimated (analogous directions as above) assuming to be located on a *peanut*-shaped surface of real combinations of spherical harmonics (1st order), val(r,ϑ,φ) with [3,7]

$$r = \lambda_1 \sin^2\vartheta \cos^2\varphi + \lambda_2 \sin^2\vartheta \sin^2\varphi + \lambda_3 \cos^2\vartheta \ .$$

The *peanut*-surface is taken as a representative for a fibre bundle that is homogenously orientated in one single direction indicated by the principal eigenvector.

Furthermore, planar cuts of the measurement planes (xy, xz, yz, i.e. transversal, coronal, sagittal, resp.) with the rotated peanut were plotted and compared to experimental data acquired within the considered plane.

Results: Fig. 1 examplarily depicts the maps of RAI[66] and colour-coded DTI, estimated from the standard tensor model. The bottom row shows the index of spherical diffusion variance (SDI) and the ratio image SDI/RAI[66]. In comparison to RAI, the SDI map - representing the measured geometric shape - highly organized white matter fibre tracts (corpus callosum, pyramidal tracts) reveal good congruence with the predicted singular fibre model. Mainly in regions of fibre crossings and the centrum semiovale, where the anisotropy index is reduced, the SDI is elevated depicting discrepancy from the tensor model.
The polar plots (Fig. 2) of the cutting planes (transversal, coronal, sagittal view) provide the possibility of rating the deviation between the assumption of a single fibre bundle and the experimental data.

Conclusion: High angular resolution diffusion-weighted imaging provides an alterntive to DSI which would require lots of more directions. With 66 directions and acceptable examination time, HARDI depicts more detailed information on white matter fibre structure DTI *a priori* cannot accomplish, and may be a good compromise for clinical imaging. Alternative weighting schemes, e. g. tightened encoding of 66 directions sampled on a hemisphere, have to be investigated, as well as representations of white matter pathologies.

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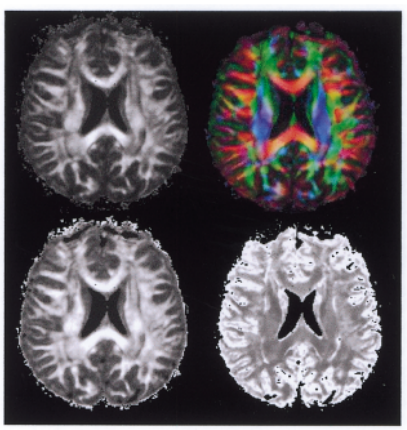

Fig. 1: a) Relative anisotropy RAI[66], b) colour-coded DTI; c) spherical diffusion variance SDI from HARDI, d) ratio SDI/RAI[66]. Hyperintensities within white matter in the ratio map indicate regions of fibre crossings.

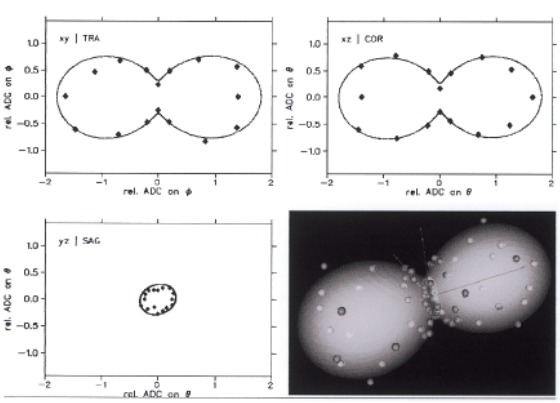

Fig. 2: Polar plots of experimental, relative ADC data and cuts of viewing planes, derived from the *peanut*-shaped representative of one principal orientation of diffusivity as proposed by the tensor diagonalization model.