Diffusion Spectrum Imaging Of Fiber White Matter Degeneration

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Introduction

White matter degeneration poses diagnostic problems in a variety of pathologies such as stroke, post-operative changes, trauma, ALS, MS and various psychological disorders. Diffusion tensor imaging (DTI) of normal white matter has been shown to reveal structure of the major white matter fascicles (1, 2). In white matter degeneration, however, DTI loose structural information and anisotropy (3-5). DTI is therefore frequently ambiguous in determining the underlying pathophysiology of white matter degeneration (6) .As white matter degeneration is tract-specific and voxels may contain multiple fiber populations (7), we may hypothesize that white matter degeneration may cause significant but not complete loss of intravoxel structure.

A new diffusion imaging method, Diffusion Spectrum Imaging (DSI) (8), directly measures the three-dimensional spin diffusion probability distribution. Using the orientational contrast in DSI intraxoxel fiber heterogeneity can be resolved, i.e., intravoxel fiber crossing in complex architecture. This characteristic increases the possibility of detecting white matter structural changes, not only in areas of known well-defined white matter anatomy, but also in areas of complex white matter anatomy.

We used diffusion spectrum imaging (DSI) to test the hypothesis that the diffusion spectrum shows residual structure in areas of Wallerian degeneration, in which DTI is featureless. Further, that fiber specific degeneration causes reduction or suppression of specific angular components of the diffusion spectrum in an anatomically meaningful way.

Methods

Diffusion spectrum imaging (DSI) is a version of 3D q-space diffusion imaging, which measures the microscopic three-dimensional spin diffusion function for each imaging voxel. DSI were obtained in healthy subjects and patients on a 3T Siemens Allegra scanner. The DSI sequence builds on an ECG gated twice refocused SE EPI sequence (9), which minimize the effects of pulsatile deformation and eddy-currents. Sequence parameters TE = 165 ms, TR = 3RR's and spatial resolution $(3mm)^3$. Six to nine slices were acquired (over 3RR intervals) in 1200 heartbeats giving an approximate imaging time of 20 min.

Analogous to Fourier encoding of position, the Fourier encoding of displacement within a three dimensional grid gives the diffusion spectrum. The spin displacements are encoded by means of auxiliary bipolar gradient pulses whose sensitivity is given by a vector $\mathbf{q}=\gamma\delta\mathbf{g}$, where $\mathbf{g}$ is the diffusion-encoding gradient, δ the time duration of the gradient, and γ is the gyromagnetic ratio. In total, 437 diffusion sensitizing $\mathbf{q}$-vectors were used to describe a uniform three-dimensional grid within a sphere. The diffusion sensitization corresponds to b-values from 0 to 20.000 s/mm^2 with isotropic spectral resolution $(2q_{max})^{-1}=4.5\mu$ and field of view $(2q_{min})^{-1}=45\mu$.

The spectra were obtained by 3D Fourier Transform of the data (Fig 1), and displayed by graphical icons, orientation density functions, representing the spectral orientations. In addition the data were fitted to a Gaussian model (diffusion tensor). As shown schematically in Fig 1, the orientational maxima of the diffusion spectra (c,d) coincide with the orientation of the fibers (a), whereas the tensor fit (e) gives a mean fiber direction in between the two true orientations (c).

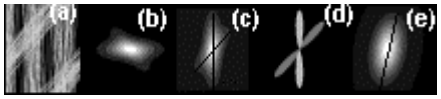


Fig 1. Fiber structure (a) gives rise to an ensemble averaged diffusion signal (b), measured by DSI. 3DFT of (b) yields diffusion spectrum (c,d). The orientation density function (d) is the diffusion spectrum integrated over radius. Tensor fit (e).

Results

We observed changes in the diffusion spectra due to Wallerian degeneration as a result of stroke and post-operative change, but no reduction in the ability to provide structural information (Fig 3). The fitted Gaussian tensor on the contrary showed isotropy and consequently no fiber structure (Fig 2). White matter degeneration seems to decrease the orientational homogeneity of the tissue resulting in an isotropic diffusion tensor. The diffusion spectrum, which does not suffer from orientational averaging, is able to show residual organized structure where the diffusion tensor fails.

Further, in areas of degeneration certain spectral maxima were either reduced or absent, indicative of fiber specific degeneration (Fig 3).

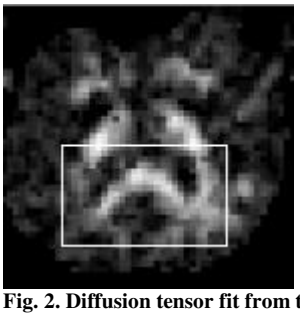


Fig. 2. Diffusion tensor fit from the diffusion spectrum data in Fig 3. Decreased anisotropy is seen in the lesion area with no apparent fiber orientation in the posterior medial portion of the optic radiation.

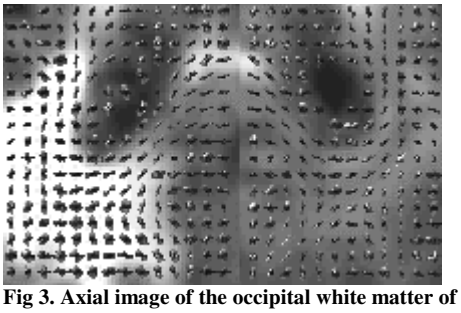


Fig 3. Axial image of the occipital white matter of a post-operative patient. The spectra suggest degeneration of the optic radiation (lesion left = patient left), and clearly show residual structure in the lesion site.

Discussion

We have shown here that three-dimensional diffusion spectrum imaging show loss of structure in a previously unrecognized complex manner. Residual structure was found in areas of white matter degeneration, indicating that white matter degeneration is localized to specific spectral components. Further, the DSI data indicate that fiber specific degeneration can be resolved. We believe that the orientational contrast of DSI will provide a better framework for detecting and investigating fiber-specific degeneration and its effect on the surrounding and intersecting white matter.

References

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