The Relation between White Matter Structures Geometry and their Diffusion Properties

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Introduction

Diffusion Tensor Imaging (DTI) is a promising technique for characterizing biological tissue microstructure and organization. In tissues with organized microstructure, such as fibrous tissues like white matter, the water diffusion is anisotropic with the direction of greatest diffusivity parallel to the fiber. DT models the diffusion using a 3D multivariate Gaussian distribution that can be represented by 3 orthogonal eigenvectors and corresponding eigenvalues [1]. The fastest diffusivity value is described by the tensor major eigenvalue, λ_1, and its orientation by the tensor major eigenvector, $\mathbf{e_1}$. The major eigenvector has been used to estimate fiber direction and has found a large range of applications, including directional color maps [2] and white matter tractography [3].

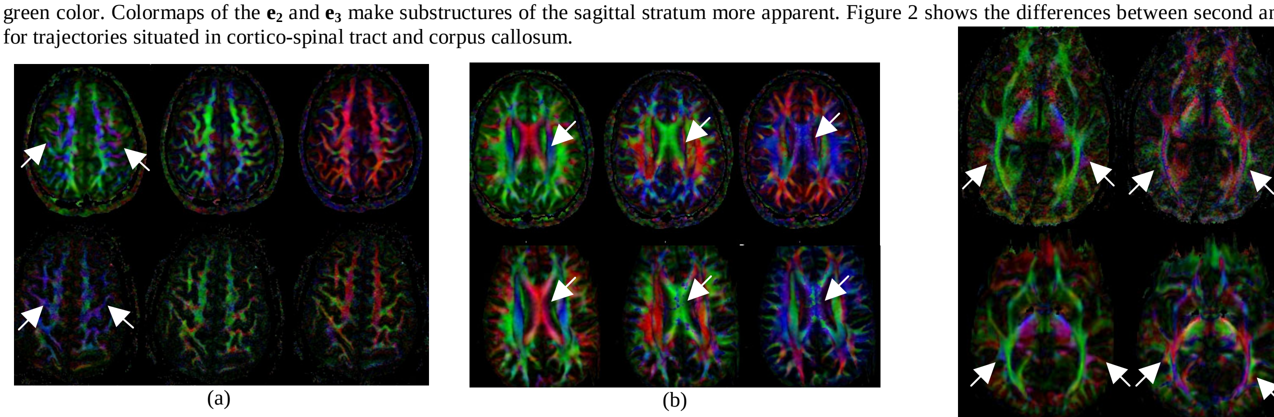
The other two tensor eigenvectors, $\mathbf{e_2}$ and $\mathbf{e_3}$, are situated in a plane perpendicular to $\mathbf{e_1}$. The diffusivity along their direction is measured by the median and minor tensor eigenvalues, λ_2 and λ_3 (with $\lambda_1 \geq \lambda_2 \geq \lambda_3$). The relative ratio of the three eigenvalues determines a variety of ellipsoidal shapes, ranging from prolate ($\lambda_1 > \lambda_2 \cong \lambda_3$), to oblate ($\lambda_1 \cong \lambda_2 \geq \lambda_3$), and spherical ($\lambda_1 \cong \lambda_2 \cong \lambda_3$). The three shapes describe cylindrical symmetric, planar, and isotropic diffusion, respectively. It was previously reported that white matter of the brain is preponderantly characterized by a combination of these shapes, which forms cylindrical asymmetric diffusion ellipsoids ($\lambda_1 > \lambda_2 > \lambda_3$) [4, 5]. The asymmetric diffusion indicates that a preferential direction of diffusion exists in the plane perpendicular to the fiber tract direction. The aim of this study was to investigate if specific patterns of "perpendicular-plane" preferential direction characterize white matter tracts, and how these patterns relate to white matter tract geometry and orientation. Color maps of the tensor eigenvectors were used to visualize their orientation.

Methods

Diffusion Tensor Imaging: DTI experiments were conducted using both 1.5 or 3T scanners. Diffusion-weighted images were obtained using a single-shot spin-echo EPI pulse sequence with diffusion sensitizing gradients applied in either 6 or 12 encoding directions [6]. The acquisition for each encoding direction was repeated 4-10 times, respectively, for magnitude averaging. Axial images were acquired to cover a 3D brain volume. The original image resolution in the three experiments was 1-2 mm in plane with 2-4 mm thick slices. Image misregistration from motion and eddy current distortion was corrected in each case using a 2D linear registration algorithm in AIR [7]. The diffusion tensor elements were estimated at each voxel [8]. The tensors eigenvalues (and the correspondent eigenvectors) were sorted as a function of the eigenvalues magnitude, and fractional anisotropy (FA) maps were calculated. White Matter Tractography was used as a means of segmenting the anatomical structures of interest. Image data was interpolated to isotropic voxel size before fiber tracking was applied. Tract seeding was performed by manually selecting region of interests (ROI) on a three-dimensional FA map. Fiber trajectories were terminated when FA became less than 0.2 or when the change in the direction exceeded 45 degrees. Data Visualization Color maps [2] have been generated for all three eigenvectors and for all subjects. Diffusion properties along several fiber tracts were plotted as a function of the distance along the tract.

Results

Axial color maps of the three eigenvectors are presented in Figures 1a-c for slices situated at the level of corona radiata, corpus callosum, and sagittal stratum. Visual inspection of images shows that color maps of $\mathbf{e_2}$ and $\mathbf{e_3}$ present structure or region-specific color patterns that are similar across subjects. For corona radiata and corpus callosum, $\mathbf{e_2}$ appears to be oriented primarily A/P (green), which correspond to the "in sheet" direction for these two structures. The main $\mathbf{e_3}$ direction is R/L (red) and S/I (blue) for corona radiata and corpus callosum, respectively. This orientation pattern is maintained for the genu (frontal) and splenium (occipital) branches of corpus callosum (that are oriented anterior-posterior) where $\mathbf{e_2}$ is oriented superior-inferior and $\mathbf{e_3}$ from left to right. Sagittal stratum can be distinguished in $\mathbf{e_1}$ color maps by its green color. Colormaps of the $\mathbf{e_2}$ and $\mathbf{e_3}$ make substructures of the sagittal stratum more apparent. Figure 2 shows the differences between second and third eigenvalues for trajectories situated in cortico-spinal tract and corpus callosum.



(a) (b) (c)

Figure 1. Color maps depicting the orientation of the principal diffusivities ($\mathbf{e_1}$, $\mathbf{e_2}$, and $\mathbf{e_3}$ from left to right) in (a) corona radiata, (b) corpus callosum, (c) sagittal stratum (see arrows), for different subjects (upper and lower row).

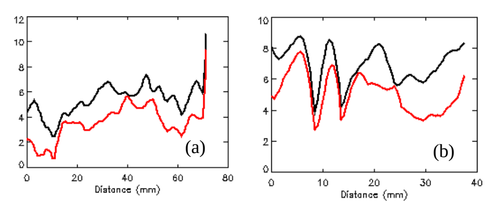


Figure 2 Median eigenvalue. λ_2 (black), and minor eigenvalue, λ_3 (red), for a corticospinal tract fiber trajectory (a) – traced from cerebral peduncle to cortex and corpus callosum (b) - traced from brain midline to cortex.

Discussion

This study shows that specific diffusivity patterns characterize the diffusion in the plane perpendicular to white matter tracts fiber orientation. In structures such as corpus callosum and corona radiata, that have a "thick sheet"-like geometry, water appears to diffuse faster in the "sheet" plane than in the direction perpendicular to the sheet. This behavior may be a consequence of fibers arranged in laminae, or of fibers crossing or diverging preponderantly into the sheet plane.

References: [1] Basser and Pierpaoli. J Magn Res B 111:209, 1996. [2] Pajevic and Pierpaoli. MRM 42:526, 1999 [3] Mori S et al. NMR Biomed 15:468, 2002; [4] Pierpaoli and Basser, Radiology 201:637, 1996 [5] Alexander et al. MRM 2000 [6] Hasan et al. J MRI, 13:769, 2001; [7] Woods et al. J Comp Ass Tom 22:141, 1998. [9] Papadakis et al. J Magn Reson.137:67, 1999.