

### 3D Tracking of Magnetic Pathways in White Matter Based on Magnetic Susceptibility Anisotropy

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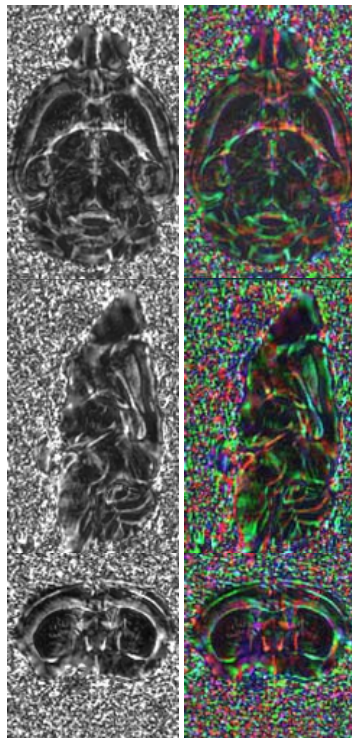
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**INTRODUCTION:** Mapping white matter fiber pathways in central nervous system (CNS) is important for the understanding of neural transmission and brain organization in general. In this study, we propose a non-diffusion based method for tracking a magnetic network existing in brain white matter. The proposed method utilizes a previously unexplored magnetic property of white matter fibers. We found that the magnetic moment of white matter varies significantly when measured at different brain orientations with respect to the external field. This orientation dependence is modeled by an apparent susceptibility tensor which is experimentally determined by the susceptibility tensor imaging (STI) technique. Decomposing this tensor into its eigensystem revealed a spatially coherent network. Following the orientation of the major eigenvector, we were able to map distinctive magnetic pathways in 3D. The relationship between the magnetic network and fiber pathways is discussed.

**METHODS:** Anisotropic susceptibility is described by a second-order (or rank 2) tensor  $\chi$  that is referred to here as apparent susceptibility tensor. The off-resonant phase of a gradient echo MR image can be found by solving Maxwell's equation. With the tensor model, we derived that the phase is expressed as in Eq. [1]. By measuring phase images at a number of different orientations, one is able to determine the apparent susceptibility tensor by inverting the system of linear equations defined by Eq. [1].

$$\theta = FT^{-1} \left\{ \frac{1}{3} \hat{H}_i \hat{H}_j FT \{ \chi_{ij} \} - k_i \hat{H}_i \frac{k_j \hat{H}_j}{k^2} FT \{ \chi_{ij} \} \right\} \gamma H_0 t \quad [1]$$

Apparent susceptibility tensor is decomposed into three eigenvalues and their corresponding eigenvectors. The three eigenvalues define three principle susceptibilities  $\chi_1$ ,  $\chi_2$ , and  $\chi_3$  ranked in a descending order. The orientations of the eigenvectors define a spatially coherent magnetic network. The procedure of fiber tracking consists of two basic components: identifying the locations of magnetic pathways and determining the pathway trajectories. The locations of magnetic



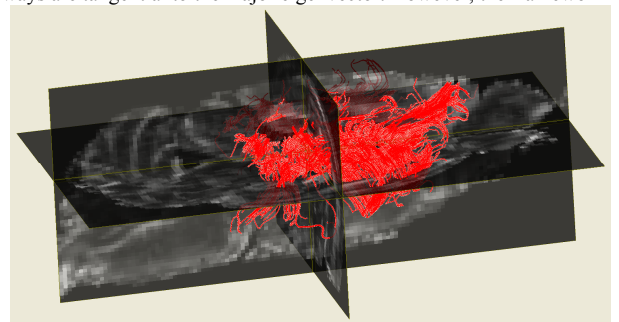
**Figure 1.** Differential susceptibility anisotropy.

pathways are identified by setting a minimum acceptable level of magnetic susceptibility anisotropy. To quantify magnetic

$$DSA = 0.5 \frac{\chi_1 - \min(\chi_1)}{\max(\chi_1) - \min(\chi_1)} + 0.5 \frac{(\chi_1 - \chi_3) - \min(\chi_1 - \chi_3)}{\max(\chi_1 - \chi_3) - \min(\chi_1 - \chi_3)} \quad [2]$$

susceptibility, we define differential susceptibility anisotropy (DSA) as in Eq. [2]. The first term in the equation is present to improve the signal-to-noise ratio. We notice that the computed apparent susceptibility tensor is a relative measure of magnetic susceptibility. In this study, the reference is chosen to be the average susceptibility of the cerebral spinal fluid. Subtracting an isotropic tensor from the apparent susceptibility tensor does not affect its eigenvectors.

Our basic hypothesis is that the magnetic pathways are tangential to the major eigenvector. However, the framework of STI tractography does not exclude other possible orientations that can be inferred from the three eigenvectors. Tracking of a specific pathway is initiated at a selected region of interest and propagated through a continuous vector field defined by the major eigenvector that is associated with the largest principle susceptibility. Tracking is only initiated when the DSA is above a certain level and is terminated when the DSA decreases to below a minimum threshold. Tracking is also terminated when the angle between two adjacent vectors is larger than a given tolerance. All tracking in this study was conducted in DtiStudio (Johns Hopkins University). This tracking algorithm can also be implemented in other existing DTI tracking software.



**Figure 2.** Examples of magnetic pathways defined by susceptibility tensor imaging.

**RESULTS:** Examples of DSA are shown in Figure 1 which demonstrates strong anisotropy in the white matter but weak anisotropy in the gray matter. To visualize the orientation of the principle axis, we further color-coded the anisotropy as: red representing anterior-posterior, green representing left-right and blue representing left-right. The observation of bulk susceptibility anisotropy in the white matter of CNS reveals a simple magnetic order beneath the incredibly complex neural tissues. An immediate implication of this magnetic network is that the long-range coherence in the principle susceptibility axis can be used to trace the direction of these magnetic pathways. One example is shown in Figure 2 with seeding points placed within the internal capsule and the hippocampal commissure.

**DISCUSSIONS AND CONCLUSIONS:** Our results reveal an intricate magnetic network within the white matter of central nervous system. Following the eigenvectors of the susceptibility tensor, we were able to define distinctive magnetic pathways. Tracking magnetic pathways in the white matter based on susceptibility tensor imaging underlies a physical principle that differs fundamentally from diffusion anisotropy (1-4). Establishing a relationship between the two, therefore, may offer a unique opportunity for method comparison and cross validation. The exact relationship is currently under investigation.

DWI/DTI is currently facing tremendous challenges at ultra-high field strength due to B1 inhomogeneity and safety concerns caused by increased RF heating. The spatial resolution of in vivo human DWI has long been limited in the range of 2-3 mm. On the other hand, phase images are routinely acquired at ultra-high field strength with a resolution higher than 0.5mm and with minimum RF heating and image distortion.

In conclusion, the proposed STI tracking approach permits the mapping of previous unknown magnetic pathways in the CNS. These magnetic pathways can be used to study white matter microstructure. In comparison to DTI tractography, the proposed STI approach provides superior spatial resolution, near distortion-free image quality and significantly lower SAR and is ideally suited at ultra high field strength.

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