Susceptibility Tensor Imaging

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INTRODUCTION: Heterogeneity of magnetic susceptibility within brain tissues creates unique contrast between gray and white matter in MRI phase images (*1, 2*). So far, susceptibility of biologic tissues has been assumed to be isotropic. In this abstract, we propose a susceptibility tensor imaging (STI) technique to measure and quantify anisotropy of magnetic susceptibility. This technique relies on the measurement of resonance frequency offset at different orientations with respect to the main magnetic field. We propose to characterize orientation variation of susceptibility using an apparent susceptibility tensor (AST). The susceptibility tensor can be decomposed into three eigenvalues (principle susceptibilities) and associated eigenvectors that are coordinate-system independent. We show that the principle susceptibilities offer strong contrast between gray and white matter while the eigenvectors provide orientation information of an underlying magnetic network. We believe that this network may further offer information of white matter fiber orientation.

METHODS: In general, magnetic susceptibility can be described by a second-order (or rank 2) tensor χ that is referred to here as apparent susceptibility tensor. For isotropic susceptibility, this tensor will be diagonal with equal diagonal elements. Given a spatial distribution of susceptibility tensors, the magnetic flux density vector **B** seen by each nucleus is related to the macroscopic flux density B_0 through Eq. [1]. Here, B_i is the *i*-th component of vector **B**; B_{0j} is the *j*-th component of vector $\mathbf{B}_0$; δ_{ij} is the Kronecker delta function; σ is the chemical shift caused by electronic screening effect. Einstein summation rule is assumed throughout this paper, that is, repeated indices are implicitly summed over.

$$B_i = (\delta_{ij} - \sigma\delta_{ij} - \frac{2}{3}\chi_{ij})B_{0j} \quad [1]$$

$$\Delta B_i = FT^{-1}\left\{\frac{1}{3}H_j FT\{\chi_{ij}\} - k_i\frac{k_{i'}H_{j'}}{k^2}FT\{\chi_{i'j'}\}\right\} \quad [2]$$

$$\theta = FT^{-1}\left\{\frac{1}{3}\hat{H}_i\hat{H}_j FT\{\chi_{ij}\} - k_i\hat{H}_i\frac{k_{i'}\hat{H}_{j'}}{k^2}FT\{\chi_{i'j'}\}\right\}\gamma H_0 t \quad [3]$$

$$\theta = FT^{-1}\left\{\frac{1}{3}FT\{\chi_{33}\} - \frac{k_3^2}{k^2}FT\{\chi_{33}\}\right\}\gamma H_0 t \quad [4]$$

Given this tensor model, the off-resonance field **ΔB** can be determined by solving Maxwell's equation. In a first-order approximation, it can be expressed as in Eq. [2]. In MRI, what we can observe is image phase or frequency offset rather than the full vector **ΔB**. The observable phase in the subject frame of reference can be expressed as in Eq. [3]. In the laboratory frame of reference, it is expressed as in Eq. [4]. Here, H_0 is the magnitude of the applied magnetic field; $\hat{H}_i$ is the unit vector along the *i*-th axis; *t* is the time of echo (TE) in a gradient echo sequence. If a sufficient number of independent measurements are available, Eq. [3] and Eq. [4] can be inverted to determine χ. In principle, both frames of reference should result in identical apparent susceptibility tensor.

As a demonstration, we conducted STI experiments on an *ex vivo* mouse brains on a small-bore 7T MRI scanner. The study was approved by the Institutional Animal Care and Use Committee. The fixed mouse brain was kept within the cranium to prevent any potential damage to the brain caused by surgical removal. The specimen was sealed tightly inside a cylindrical tube. To allow free rotation, the tube was contained within and taped to a hollow sphere. The sphere containing the specimen was placed inside a dual-channel mouse coil. High resolution 3D SPGR images were acquired using the following imaging parameters: matrix size = 256x256x256, field-of-view (FOV) = 22x22x22 mm^3, flip angle = 60°, TE = 8 ms, and TR = 100 ms. After each acquisition, the sphere was rotated to a different orientation and the acquisition was repeated. A total of 19 orientations were sampled which roughly cover the spherical surface evenly. Images were coregistered in Matlab (Mathworks Inc., MA).

RESULTS: The measured susceptibility tensor is decomposed into three eigenvectors and three associated eigenvalues denoted as χ_1, χ_2, and χ_3 in a descending order. Examples of eigenvalue maps and the corresponding mean susceptibility maps are shown in Figure 1. The maximal principle susceptibility $\chi_1$demonstrates the strongest contrast between gray and white matter. In fact, the maximal principle susceptibility provides a contrast that is strikingly similar to fractional anisotropy map computed by diffusion tensor imaging (*3*). The maximal principle susceptibility is further color-coded based on the direction of the associated eigenvector with red representing anterior-posterior, green representing left-right and blue representing superior-inferior. The color-coded principle susceptibility is shown in Figure 1.

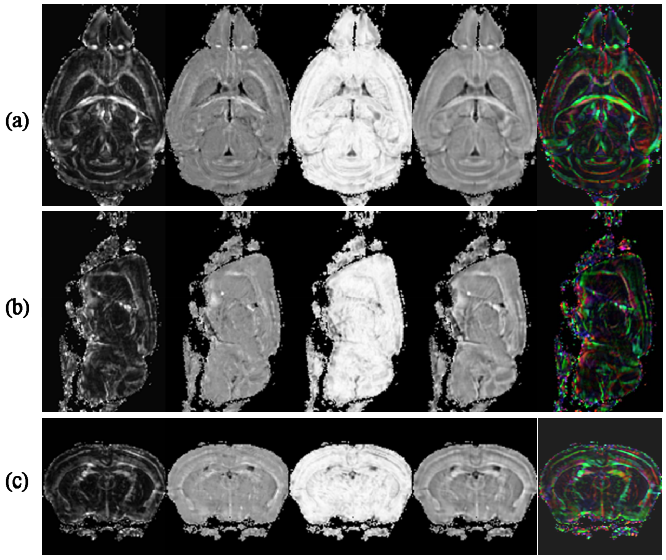

Figure 1. Principle susceptibility and mean susceptibility maps. (a) Shown from left to right are the maximal principle susceptibility, the median principle susceptibility, the minimal principle susceptibility, the mean susceptibility respectively and color-coded maxmimal principle susceptibility of an axial slice, (b) of a sagittal slice and (c) of a coronal slice. The maximal principle susceptibility offers the strongest contrast between gray and white matter that is similar to diffusion fractional anisotropy.

DISCUSSIONS AND CONCLUSIONS: Our results show that magnetic susceptibility anisotropy can be effectively described by a second order tensor. One advantage of the tensor description is that coordinate independent quantities can be defined through eigenvalue decomposition. The resulting principle susceptibility maps not only provide a quantitative measure of magnetic susceptibility anisotropy but also offer a unique image contrast.

Because of tissue heterogeneity, tensor values will be different for different tissues, thus providing a unique mechanism to enhance tissue contrast. This contrast can be displayed as tensor elements, eigenvalues and eigenvectors, or a combination of them such as a magnitude image weighted by eigenvalues. Tissue structural changes caused by tumor, stroke, traumatic injury and iron-content changes caused by developmental iron deficiency and aging will then manifest in the changes of those quantities. Furthermore, susceptibility anisotropy is not only an intrinsic property of brain tissue; it can also be potentially induced by the introduction of exogenous molecular agents.

Another important potential application of STI is for mapping 3D white matter fiber pathways in the CNS.

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