

Feasible 3-orientation acquisition for detecting susceptibility anisotropy in the human brain using prior structural information

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Introduction: Susceptibility tensor imaging (STI) (1) reported in one human brain required 12 different orientations of the head (2), which are very difficult to perform even in the most cooperative volunteers and are impractical to perform in patients. The general STI problem with 6 unknowns is ill-posed and requires the acquisition of many orientations. This number of unknowns can be reduced by imposing a cylindrically symmetric susceptibility tensor (CSST) (3). The CSST may share the orthonormal basis with the diffusion tensor obtained from DTI. Here we demonstrate the feasibility of using this prior information to construct a susceptibility tensor using only 3 orientations, examine the effects of imposing cylindrical symmetry, and report initial experience in a group of human subjects.

Theory: DTI provides the coordinate transformation R between the subject frame and the tensor orthonormal basis: the susceptibility tensor in the subject frame $\vec{\chi}$ is $\vec{\chi} = R^T \vec{\chi}_T R$, where $\vec{\chi}_T = \text{diag}(\chi_{||}, \chi_{\perp}, \chi_{\perp})$ is the CSST in the tensor orthonormal basis (Fig. 1). The forward problem in k space is that the measured local field relative to B_0 (ΔB) is the magnetization induced by a unit applied field $(\vec{\chi} \cdot \vec{B}_0)$ multiplied by the dipole kernel, $\Delta B = \frac{\vec{\chi} \cdot \vec{B}_0}{3} - \vec{k} \cdot \vec{B}_0 \frac{\vec{k} \cdot (\vec{\chi} \cdot \vec{B}_0)}{k^2}$. The inverse problem is solved as

$$\vec{\chi}(\mathbf{k}) = \text{argmin}_{\vec{\chi}(\mathbf{k})} \sum_{p,r} \left| \mathbf{w}_p(\mathbf{r}) [\text{FT}^{-1}(\Delta B_p(\mathbf{k})) - \text{FT}^{-1} \left(\frac{\vec{\chi} \cdot \vec{B}_{0p}}{3} - \vec{k} \cdot \vec{B}_{0p} \frac{\vec{k} \cdot (\vec{\chi} \cdot \vec{B}_{0p})}{k^2} \right)] \right|^2.$$

Here p is the index of the orientation of the subject head w.r.t. B_0 , and $\mathbf{w}_p(\mathbf{r})$ is a weighting according to SNR in the p^{th} orientation. This solver is generally applicable for STI, with and without symmetry.

Methods: For validation, a phantom was constructed using a bundle of parallel carbon fibers with a known CSST (4) in an agarose background and imaged with a multiple echo gradient echo (MEGRE) sequence in an 8 channel head coil with 12 evenly distributed orientations over a sphere. A total of 5 volunteers (aged 26.4 ± 1.8 yrs) participated in this IRB approved study. The subjects were asked to hold their heads with various left-right and forward- back orientations in supine and prone positions. Brain STI data was acquired at each orientation using the MEGRE sequence and a large bird cage head coil on a 3T scanner. 33-direction EPI DTI was acquired and registered with STI data with FLIRT and FUGUE (5). The inverse of susceptibility anisotropy degree (AD) was calculated as $AD = \ln(|\lambda_3|/|\lambda_1|)$, where the eigenvalues λ_i are ordered from high to low (6). When the natural log is taken $AD=0$ for isotropic tensor. AD was measured in the corpus callosum and internal capsules of all subjects. Summary

statistics and the p-value of a paired t test between 13 and 3 orientations in the same subject were obtained from AD maps.

Results: The eigenvalues (Fig.2) and AD values were similar in STI and CSST reconstructions of the carbon fiber phantom ($AD = -2.35 \pm 1.66$ and -2.62 ± 0.99 respectively). We succeeded in the 3-orientation acquisition in all 5 subjects in supine and the full 13-orientation acquisition only in 1 subject with both supine and prone positions. The CSST between 3 and 13 orientations (Figs.3a&b) showed similar AD values ($p > .05$) for both corpus callosum and internal capsules; The AD maps of CSST and STI at 13 orientations (Figs.3b&c) showed similar pattern but different values ($p < .05$) for both brain regions (Table 1).

Discussion: CSST is similar to STI when there is cylindrical symmetry in the susceptibility tensor, as confirmed in the carbon fiber experiment (Fig.2). Visually the 3-orientation and 13-orientation CSSTs and the 13-orientation STI demonstrated similar susceptibility anisotropy pattern in the AD maps, and the 3-orientation CSST is surprisingly not that much noisier than the 13-orientation CSST (Fig.3). Cylindrical symmetry and the DTI principal eigenvector may be used to generate a susceptibility tensor from data of only 3 orientations that are fairly well tolerated by cooperative subjects, which may be useful for detecting susceptibility anisotropy in the human brain.

The quantitative differences in AD between CSST and STI in human brain may be caused by either the bias in the poorly posed STI due to the limited range of orientations near the SI direction in the data acquisition and/or the inadequacy in the approximation of cylindrically symmetry used in CSST. Further work is required to sort out these issues and evaluate the applicability of the cylindrical symmetry for human brain susceptibility anisotropy study.

Ref: [1] Liu, MRM:63:1411-7, 2010. [2] Li et. al., Proc. ISMRM:19:2011. [3] Wharton et. al., Proc. ISMRM:19:4515:2011. [4] Kimura et. al., JAP:40:2237-40:2001. [5] Smith et. al., NeuroImage:23:S208-S219:2004. [6] Jelinek, Tectonophysics:79(3-4):T63-T67:1981

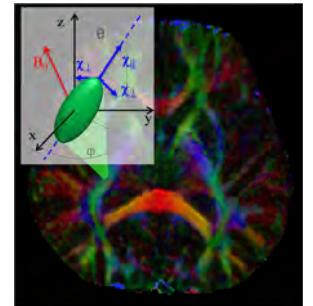


Fig. 1: Relation between DTI and STI ellipsoid.

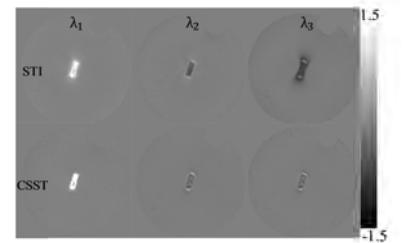


Fig. 2: Eigenvalues in the carbon fiber phantom (ppm)

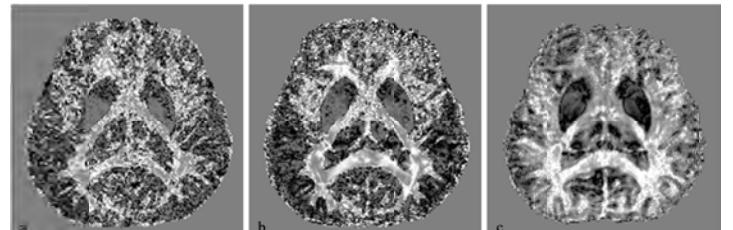


Fig. 3: AD maps from the same volunteer, a, CSST from 3 orientations, b, CSST with 13 and c, STI with 13 orientations

Table 1: Measured anisotropy of white matter

Susceptibility Anisotropy Degree	13 CSST		3 CSST		13 STI	
	Mean	SD	Mean	SD	Mean	SD
Corpus Callosum	1.00	0.64	0.84	1.51	2.15	1.00
Internal Capsules	0.87	0.75	0.92	1.17	0.47	0.3