How Well Can Magnetic Susceptibility Anisotropy be Estimated? An Error Analysis of Cylindrically Symmetric Susceptibility Tensor Reconstructions from Few Orientations

Cynthia Wisnieff[1], Pascal Spincemaille[2], Tian Liu[3], and Yi Wang[1]

[1]*Cornell Univerisity, New York, New York, United States,* [2]*Weill Cornell Medical College, New York, New York, United States,* [3]*Medimagemetric, New York, New York, United States*

Target Audience Anyone interested in white matter anisotropy

Introduction: Imaging magnetic anisotropy of white matter with susceptibility tensor imaging, STI, has been pursued as an alternative biomarker of myelin organization [1-3]. Further examination of STI *in vivo* has been hampered by the scan time and difficulty in acquiring the many-orientation data necessary for estimating the magnetic susceptibility anisotropy (MSA). Applying constraints can reduce the number of unknowns in susceptibility tensor, making it possible to estimate the MSA in human subjects with fewer orientations [4-6]. Here, we report an error analysis in the cylindrically symmetric constrained susceptibility tensor (CSST) reconstruction, pointing out the potential and pitfalls of this CSST approach.

Methods*:* *CSST* is an inverse solution to

$$\Delta(\mathbf{k}) = \frac{\hat{\mathbf{b}}\cdot\left(FT(\mathbf{R}^{\mathrm{T}}\chi_T\mathbf{R})\cdot\hat{\mathbf{b}}\right)}{3} - \hat{\mathbf{b}}\cdot\mathbf{k}\,\frac{\mathbf{k}\cdot\left(FT(\mathbf{R}^{\mathrm{T}}\chi_T\mathbf{R})\cdot\hat{\mathbf{b}}\right)}{\mathbf{k}^2}$$

, Eq.1 where Δ is the relative difference field in k-space, $\chi_T = \mathrm{diag}(\chi_\perp, \chi_\perp, \chi_\parallel)$ in the tensor frame, $\hat{\mathbf{b}}$ is the B_0 direction relative to subject orientation, and $\mathbf{R}$ is the rotation from the tensor frame to the subject frame.

Condition Number (κ *)* is an indicator of the worst case error amplification in solving Eq.1. κ*'s* were computed exactly for 560 combinations of 3 orientations out of 16 orientations uniformly distributed over a sphere with a matrix size of 32x32x32.

Human brain numerical phantom was constructed with uniform anisotropy of 0.02ppm imposed over white matter regions. The numerical phantom was sampled with 1) 12 orientations uniformly distributed over a sphere (uniform 12), 2) 12 human feasible orientations (human 12), and 3) 3 human feasible orientations (human 3). CSST was constructed for these 3 simulated acquisitions.

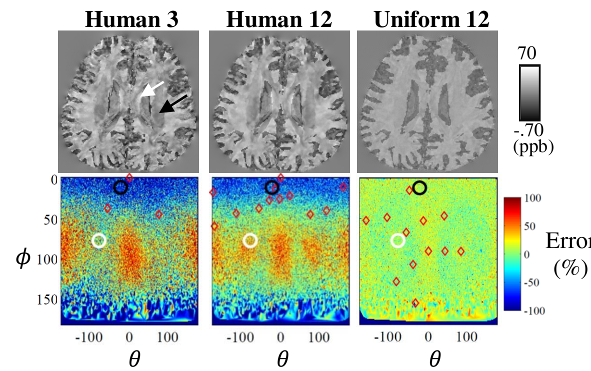
Human MRI (n=4 with IRB approval) was performed with 3 orientation multi-echo gradient echo (MEGRE) with a 1.5mm^3 isotropic resolution (TR/spacing/#Echoes=46.9ms/2.6ms/11) and a diffusion tensor imaging (DTI) acquisition (33 directions @b=1000s/mm^2 + reference) on a GE 3T clinical scanner for 3CSST reconstruction. One volunteer was able to perform an additional 9 orientations MEGRE for a total of 12 orientations for 12-CSST.

Results:

Condition Number κ was infinite for a set of 3 orientations that were aligned in a plane; κ min/median/max =9.4×10^3/ 3.2×10^5/ 3.1×10^{11} for the remaining 559 sets, 20 of which were human feasible with κ min/median/max =2.0×10^4/ 7.1×10^5/ 1.8×10^8.

Human brain numerical phantom results showed that while uniform orientations allowed reliable MSA estimation, human orientations (both 3 and 12) had substantial underestimation of MSA for superior-inferior (SI) fibers (ϕ=0/π in Fig.1) and over estimation for anterior-posterior (AP) fibers (θ=0/π).

Human MRI reconstructed 3-CSST in all subjects showed consistent MSA measured in the body (BCC) and splenium (SCC) of the corpus callosum and the optic radiations (OR), agreeable with 12-CSST as shown in Fig.2 when these fibers are not along SI or AP.



MSA Error Dependence on Fiber Orientation

Fig. 1: Estimation of white matter MSA using realistic fiber orientations with various CSST reconstructed MSA (top row) and associated errors (bottom row). Red diamonds in the error maps represent the directions in each of the corresponding MSA maps in the top row. The white and black circles in the error maps correspond to the regions indicated by the white and black arrows in the MSA maps respectively.

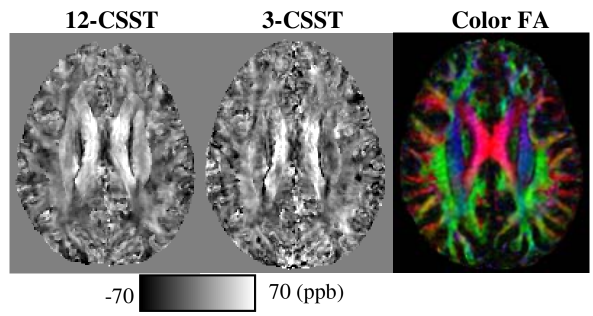


Fig. 2: 12CSST and 3CSST MSA maps in the volunteer with 12 orientations and the color FA.

Table 1:Measurements of MSA across volunteers, ppb

	SCC	BCC	OR
Subject 1	5 ± 21	20 ± 38	30 ± 24
Subject 2	14 ± 12	31 ± 24	30 ± 22
Subject 3	8 ± 16	22 ± 23	31 ± 22
Subject 4	-7 ± 18	37 ± 24	27 ± 23

Discussion and Conclusion:

Our condition number and error analysis data show that CSST is highly sensitive to relative angles between fiber and acquired orientations. It is possible to consistently reconstruct the CSST with as few as 3 orientations for white matter fibers along the left-right direction but not in the SI and AP directions for human feasible yaw positions (head tilts).

References:1. Li, W., B. Wu, and C. Liu, Proc. Intl. Soc. Mag. Reson. Med., 2011. **19**: p. 121.2. Li, W., et al., NeuroImage, 2012. **59**(3): p. 2088-97.3. Wharton, S. and R. Bowtell, Proc Natl Acad Sci U S A, 2012. **109**(45): p. 18559-64.4. Li, X., et al., NeuroImage, 2012. **62**(1): p. 314-30.5. Wharton, S. and R. Bowtell, Proc. Intl. Soc. Mag. Reson. Med., 2011. **19**: p. 4515.6. Wisnieff, C., et al. in *Proc. Intl. Soc. Mag. Reson. Med.* 2012. Melbourne.