# In vivo Evidence of Susceptibility Anisotropy and Susceptibility Tensor Imaging of Human Brain

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**INTRODUCTION:** Susceptibility mapping is emerging as a powerful tool to utilize imaging phase to visualize the delicate anatomical details of the human brain. The application of susceptibility mapping in the study of gray matter, especially the iron rich deep nuclei, has been well demonstrated in previous studies. In addition to gray matter, susceptibility maps also shows excellent contrast of white matter. However, unlike the homogenous property of gray matter, the white matter has highly organized microstructures. Previously, it is generally assumed that susceptibility of brain tissue is isotropic. Until recently, emerging evidences started to show that the phase/susceptibility contrast is actually dependent on fiber orientation. He et al reported that phase contrast is dependent on white matter fiber orientation (1). Duyn and colleagues also reported the orientation dependence of susceptibility using *in vitro* preparations of human corpus callosum stripes (2). At the same time, Liu observed the anisotropic magnetic susceptibility in mouse brain and quantified the susceptibility anisotropy comprehensively with a tensor model (3). In this study, we demonstrated the evidence of magnetic susceptibility anisotropy from in vivo human brain, and further compared the three primary eigenvalues of susceptibility tensor.

**MATERIALS AND METHODS**

*Brain MR Imaging***:** High-resolution gradient echo images of the brain of a healthy human subject was scanned on a GE MR750 3.0T scanner equipped with an 8-channel head coil using a standard flow-compensated 3D spoiled-gradient-recalled (SPGR) sequence with TE = 42 ms, TR = 60 ms, flip angle = 20º, FOV = 256x256x180 $mm^3$, matrix size = 256x256x180. Diffusion tensor images (DTI) were also acquired using a standard single-shot EPI sequence with TE = 82 ms, TR = 8 s, FOV = 256x256 $mm^2$, matrix size = 128x128, slice thickness = 2 mm without gap, b-value = 800 $s/mm^2$, 5 non-diffusion weighted images and 32 diffusion encoding directions. Eleven additional sets of SPGR images with reduced spatial resolution (2x2x2 $mm^3$) using a larger single-channel head coil were also acquired with different brain orientations with respect to the main magnetic field from a different healthy human subject.

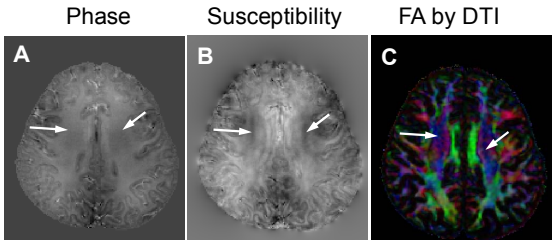

Fig. 1. Comparison between phase/susceptibility and FA map obtained from DTI. Blue color: superior-inferior direction.

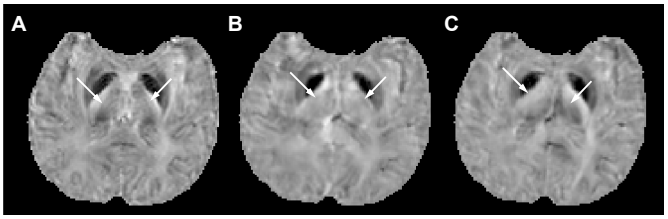

Fig. 2. Apparent magnetic susceptibility from different orientations

*Image Analysis***:** The image phase was unwrapped with a Laplacian based method (4) and filtered with the sphere mean filtering method (5). The magnetic susceptibility was quantified using the high resolution single-orientation phase data by the weighted k-space derivative method (4). The resultant susceptibility map was compared with the fractional anisotropy (FA) maps obtained by DTI. Multiple orientation images were linearly registered using FSL-FLIRT. Susceptibility map were first reconstructed using single-orientation method assuming isotropic susceptibility. The directionality of susceptibility is observed. Hence, the susceptibility tensor model (3) is applied to the multiple orientation phase data to recalculate the magnetic susceptibility. The principal eigenvalues of susceptibility tensor were calculated. Since susceptibility is a relative value due to the removal of background phase, all the primary susceptibility eigenvalues were normalized assuming isotropic susceptibility in the cerebrospinal fluid and white matter.

**RESULTS:** Unlike phase images (Fig. 1A) with reasonably homogenous contrast in the white matter, the magnetic susceptibility of the white matter calculated with the single-orientation method is heterogeneous (Fig. 1B). The arrows point to a number of selected white matter fiber bundles that run approximately in the superior-inferior direction, i.e., in parallel to the main magnetic field. The susceptibility of these particular fibers appears to be significantly more paramagnetic compared to that of the surrounding white matter fibers of different orientation. This pattern of the inhomogeneity seems to be correlated with FA map determined by diffusion tensor imaging (Fig. 1C). Susceptibility map of brain were also calculated with various brain orientations with respect to the main magnetic field (Fig. 2). As pointed by the arrows, the susceptibility contrast between white matter and gray matter indeed showed significant difference between different orientations. Hence, the susceptibility tensor is calculated from the multi-orientation data (3). Significant difference between gray matter and white matter were observed among the different principal susceptibility eigenvalues. These results provide convincing evidences that white matter susceptibility is anisotropic.

**CONCLUSION:** In this study, we demonstrated that the magnetic susceptibility of in vivo brain white matter is anisotropic. In addition to its importance in the application of susceptibility mapping to study white matter structures, this anisotropic property also provides the possibility to measure the fiber orientation of brain white matter other than diffusion tensor imaging.

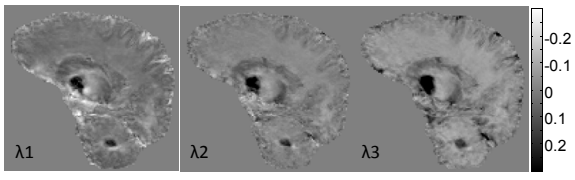

Fig. 3. Principal eigenvalues of susceptibility tensor (ppm)

**REFERENCES**: (1) He and Yablonskiy, PNAS, 2009. (2) Lee et al, PNAS 2010. (3) Liu, MRM 2010. (4) Li et al, manuscript in revision. (5) Schweser et al, Proc. ISMRM, 2010.