Susceptibility Mapping of Human Brain Reflects Spatial Variation in Tissue Composition

W. Li[1], B. Wu[1], and C. Liu[1,2]
[1]Brain Imaging & Analysis Center, Duke University, Durham, NC, United States, [2]Radiology, Duke University, Durham, NC, United States

INTRODUCTION: Image phase contains unique information regarding tissue composition. However, phase is limited by its non-local, orientation dependent properties so that the measurement based on phase is not easily reproducible. Hence, it is of great interest to determine the intrinsic property of the tissue, i.e. the magnetic susceptibility, from phase. The quantification of susceptibility from phase images is a well known ill-posed problem due to the zero-coefficients on two conical surfaces for susceptibility mapping. Here, we developed a novel susceptibility mapping method using weighted k-space first-order derivatives. The derivative relationship at the conical surfaces provides an effective complement to original equation for susceptibility mapping so that the zero-coefficient scenario is significantly reduced. This method allows high quality reconstruction of susceptibility maps using single-orientation phase data.

THEORY: Define $\psi(\mathbf{r})=\Delta\varphi/\gamma H_0 TE$, the ψ can be calculated for any susceptibility distribution, $\chi(\mathbf{r})$, in frequency domain by $\psi(\mathbf{k})=D_2(\mathbf{k})\cdot\chi(\mathbf{k})$, where $\mathbf{k}$ is the spatial frequency vector and $D_2(\mathbf{k})=(1/3-k_z^2/k^2)$. Incorporate a binary brain mask, M_{brain}, the following relationship between $\psi(\mathbf{r})$ and $\chi(\mathbf{r})$ can be obtained:

$$FT\left[M_{brain}\cdot\psi(\mathbf{r})\right]=FT\left[M_{brain}\right]\cdot D_2(\mathbf{k})\cdot\chi(\mathbf{k}) \quad (1)$$

Here, FT refers to Fourier transform. Although $D_2(\mathbf{k})=0$ on the conical surfaces, its derivative is not. The derivative relationship can be written as follows:

$$M_{D3}\cdot FT\left\{M_{brain}\cdot FT^{-1}\left\{D_3(\mathbf{k})\cdot\chi(\mathbf{k})+D_2(\mathbf{k})FT\left[ir_z\chi(\mathbf{r})\right]\right\}\right\}=M_{D3}\cdot FT\left[ir_z M_{brain}\psi(\mathbf{r})\right] \quad (2)$$

where $D_3(\mathbf{k})=(k_x^2+k_y^2)k_z/\pi k^4$, and M_{D3} is a continuous weighting coefficient for the derivative relationship. The two equations were solved with LSQR method to reconstruct the susceptibility map, $\chi(\mathbf{r})$.

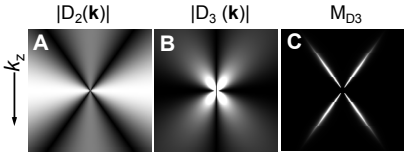

Fig. 1. Magnitude of D_2, D_3 and M_{D3}

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.

Image Analysis: The brain tissue was extracted using ITK-SNAP (1). The phase from each coil was unwrapped and then averaged. The background phase were removed using the spherical mean filtering (2). Susceptibility map was then calculated from the phase.

RESULTS: Fig. 1 shows the magnitude of $D_2(\mathbf{k})$, $D_3(\mathbf{k})$ and M_{D3}. The magnitude of $D_2(\mathbf{k})$ shows the zero-coefficient cone as defined by $k^2=3k_z^2$ (Fig. 1A), while such zero-coefficient cone is absent in the magnitude of $D_3(\mathbf{k})$ (Fig. 1B). These results demonstrate that the derivative relationship (Eq. 2) complements the original equation (Eq. 1). The continuous weights for derivative operation (M_{D3}) were shown in Fig. 1C. Susceptibility (Fig. 2 E&F) was calculated from the phase (Fig. 2 C&D). The susceptibility map shows excellent image quality with no obvious streaking artifact. In the brain, the iron-rich structures, including putamin (Pu) globus pallitus (GP) and dentate nucleus (as well as red nucleus, substantia nigra, not shown), displayed strong paramagnetic shift comparing to the surrounding tissue. The susceptibility map also shows excellent gray/white matter contrast. The white matter structures, such as splenium of the corpus collosum (scc), capsula interna (CI) and sagittal stratum (SS) can be easily distinguished from surrounding gray matter due to the diamagnetic properties of myelin of the axon fibers.

DISCUSSION AND CONCLUSION: We developed a novel susceptibility mapping method using the weighted k-space derivatives, which allows high quality susceptibility mapping of human brain *in vivo*. The resulting susceptibility maps provide a unique quantitative contrast that reflects spatial variation in tissue composition. The iron rich deep nuclei were darker than surrounding tissue due to the paramagnetic properties of the tissue iron, while the white matter fiber bundles was brighter than surrounding gray matter due to the diamagnetic properties of the myelin. This method is robust and efficient, thus providing a convenient tool for routine non-invasive assessment of tissue composition, especially iron and myelin content, which are very important for the evaluation of many neurological diseases.

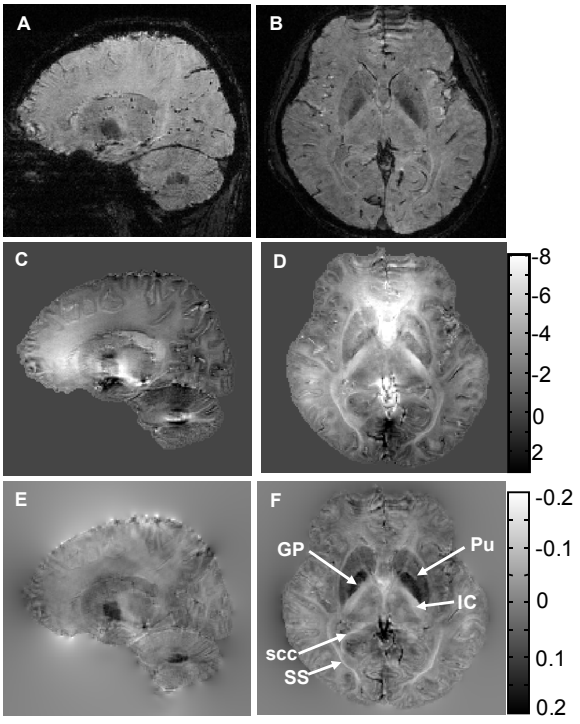

Fig. 2. Comparison between magnitude (A&B), frequency shift (Hz) (C&D) and susceptibility (ppm) (E&F).

References: (1) Yushkevich et al. NeuroImage, 2006 (2) Schweser et al, NeuroImage, 2010