HARPERELA Phase Processing for Quantitative Susceptibility Mapping

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AUDIENCE: Any researcher interested in Quantitative Susceptibility Mapping (QSM) and Susceptibility Tensor Imaging (STI).

INTRODUCTION: Quantitative susceptibility mapping (QSM) is a recently developed MRI technique that provides a quantitative measure of tissue magnetic susceptibility. It requires reliable 3D phase unwrapping and removal of background susceptibility contributions. These two steps are typically performed separately. Here we present a method that simultaneously performs phase unwrapping and HArmonic (background) PhasE REmovaL using LAplacian, which is named as HARPERELLA. HARPERELLA is fast, robust and yields local tissue phase with similar accuracy to the well-known sophisticated harmonic artifact reduction for phase data (SHARP) (1) and the projection onto dipole fields (PDF) (2) methods. The HARPERELLA algorithm is provided together with QSM, STI algorithms, and related graphical user interfaces in a software package, namely "**STI Suite**", which is available online at http://people.duke.edu/~cl160/.

MATERIALS AND METHODS:

Theory: The Laplacian of the phase can be derived from sine and cosine functions of the wrapped phase using Fourier transforms (3,4):

$$\nabla^2\varphi = -4\pi^2\cos\varphi\cdot FT^{-1}\left[k^2FT(\sin\theta)\right]+4\pi^2\sin\varphi\cdot FT^{-1}\left[k^2FT(\cos\theta)\right] \qquad [1]$$

To solve Eq. [1] using Fourier transforms, we estimated the phase Laplacian outside the tissue using a spherical mean value (SMV)-based approach. The field of view (FOV) is divided into three different regions: regions *I, O* and *E* (Fig. 1). The unknown phase Laplacian in region *E* ($\nabla^2\varphi_E$) is estimated by solving the following minimization problem:

$$\min_{\nabla^2\varphi_E} \left\| S(\nabla^2\varphi_E)+S(\nabla^2\varphi_{I+O})-\delta\right\|_2 \qquad [2]$$

where "S" represents the SMV operator, and the residual susceptibility sources δ are estimated as the mean over trustable region *I*.

Once φ_E is determined, the background removed phase can be obtained using the following FFT-based inverse Laplacian:

$$\varphi = -FT^{-1}\left[FT(\nabla^2\varphi_{I+O}+\nabla^2\varphi_E)/4\pi^2k^2\right] \qquad [3]$$

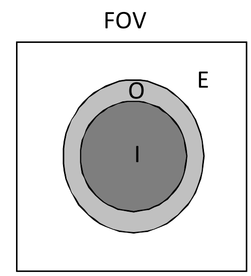

Fig. 1. A diagram of the different regions in the FOV: *I* and *O* are interior and boundary regions of the brain, respectively, and *E* is the exterior of the brain that are within a distance of the spherical kernel radius.

Brain Imaging and analysis: In vivo brain imaging of 10 adult subjects was conducted on a GE MR750 3.0T scanner (GE Healthcare, Waukesha, WI) equipped with an 8-channel head coil. Phase images with whole-brain coverage were acquired using a standard flow-compensated 3D Fast spoiled-gradient-recalled (FSPGR) sequence with the following parameters: TE = 23 ms, TR = 30 ms, flip angle = 20º, field-of-view (FOV) = 256x256x176 mm^3, matrix size = 256x256x176, SENSE factor = 2.

The background phase was removed using HARPERELLA. Briefly, the Eq. [2] is solved using the LSQR method, using a spherical kernel radius (R) of 10 mm. The background removed phase was calculated using Eq. [3] followed by zero filling regions outside the brain. The method was then compared with a modified SHARP method with varying spherical mean kernel size (V-SHARP) (5) and the PDF method. We compared their accuracy for qualifying the mean magnetic susceptibility of several selected brain structures in 10 subjects.

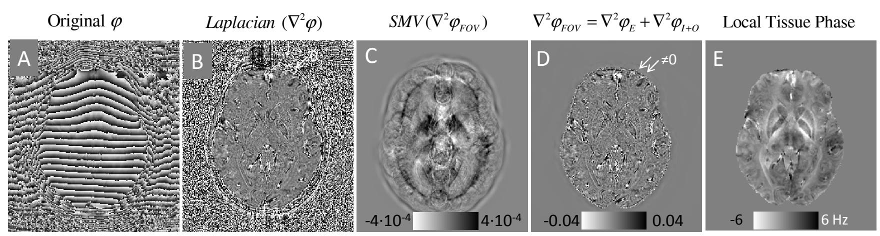

Fig. 2. HARPERELLA phase processing. A: Raw phase. B: Laplacian of the raw phase. C: The spherical mean value of a Laplacian distribution that satisfies Eq. 2. D: the optimal phase Laplacian calculated using Eq. 2. E: the final unwrapped phase free of background phase.

RESULTS AND DISUSSION:

From Fig.2, the local tissue phase can be extracted from the raw phase using HARPERELLA with R=10mm. We varied the spherical kernel radius from 1 mm to 16 mm, we found that the background removal using radius ranging from 6mm to 16 mm are all satisfactory. For the brain tissue, all inaccurate Laplacian values are located at the boundary. These errors are compensated using the optimized $\nabla^2\varphi_E$. In this compensation, the voxels close to brain boundary play more important roles. Therefore, after a necessary threshold is reached, the size of SMV kernel will not affect the results significantly.

From Fig. 3, the HARPERELLA yield very similar tissue phase and the subsequent magnetic susceptibility maps as V-SHARP and PDF. Quantitatively, the magnetic susceptibility using HARPERELLA processed phase are linearly correlated with those derived from V-SHARP (slope = 0.95, R2=0.98) and those calculated using PDF (slope = 0.97, R2=0.95). This is due to the fact that all three methods are based on the same physical principles and only removes the harmonic phase that satisfies the Laplace equation.

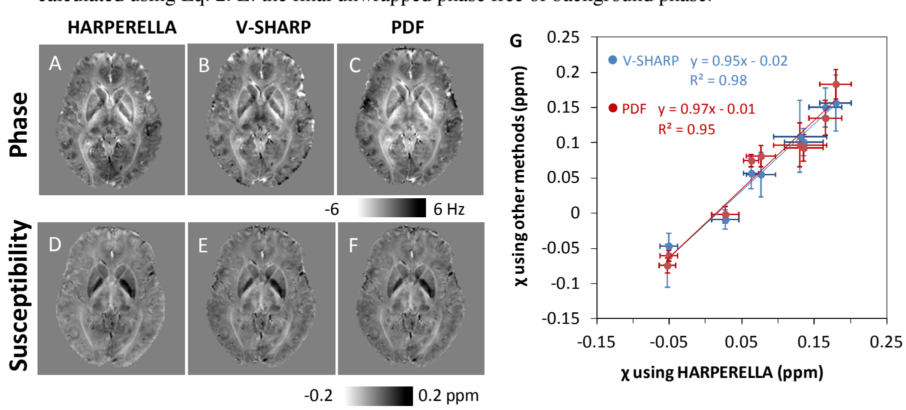

Fig. 3. Comparison of HARPERELLA with V-SHARP and PDF. A-C: Local tissue phase obtained using HARPERELLA, V-SHARP, and PDF respectively. D-F: Corresponding magnetic susceptibility maps. G: Comparison of the magnetic susceptibility values using the three different methods. The regions of interest includes: putamen, globus pallidus, caudate nuclei, red nuclei, substantia nigra, dentate nuclei, internal commissure, splenium of the corpus callosum and optic radiation.

CONCLUSION: We developed a novel method, named as HARPERELLA, for integrated phase unwrapping and background phase removal using the Laplacian operator. With the same underlying physical principles, HARPERELLA yields similar local tissue phase as V-SHARP and PDF, and allows quantification of magnetic susceptibility of various brain structures with similar accuracy. We provided our HARPERELLA, QSM, STI algorithms and related graphical user interfaces in a software package, i.e. "STI Suite", for free academic use.

REFERENCES: (1) Schweser et al, NeuroIamge 2011; (2) Liu et al, NMR Biomed 2011 (3) Schofield and Zhu, Opt Lett 2003 (4) Li et al, NeuroImage 2011. (5) Wu et al, MRM 2011.