Phase-Based Quantification of Magnetic Susceptibility in Healthy Volunteers and Patients with Neurological Disorders at 7T

K. E. Hammond[1], J. M. Lupo[2], S. Banerjee[2], D. A. Kelley[3], D. B. Vigneron[1,2], S. M. Chang[4], P. Mukherjee[5], and S. J. Nelson[1,2]

[1]University of California San Francisco (UCSF) / Berkeley Joint Graduate Group in Bioengineering, San Francisco, CA, United States, [2]Surbeck Laboratory, Radiology, UCSF, [3]GE Healthcare, [4]Neurosurgery, UCSF, [5]Neuroradiology, UCSF

Introduction: This study presents a technique for calculating magnetic susceptibilities (χ) from the phase of gradient-recalled echo (GRE) images. While researchers have known for years that χ-effects of iron and calcium are visible in GRE phase images of patients with neurological disorders [1-3], this study is the first to calculate the χ. The 7T field strength enables scanning at a spatial resolution that captures the B0 field distortions from small features such as hemorrhages adequately enough for comparison with theoretical models of χ-effects on the B0 field. This study presents applications going both from phase to χ and from χ to phase. The first application uses phase to calculate χ in suspected hemorrhages and calcifications. The second application uses theoretical χ-effects to search for hemorrhages in the phase images. Detection and characterization of hemorrhages and calcifications is clinically relevant as a surrogate for brain injury following trauma or brain injury secondary to therapeutic radiation.

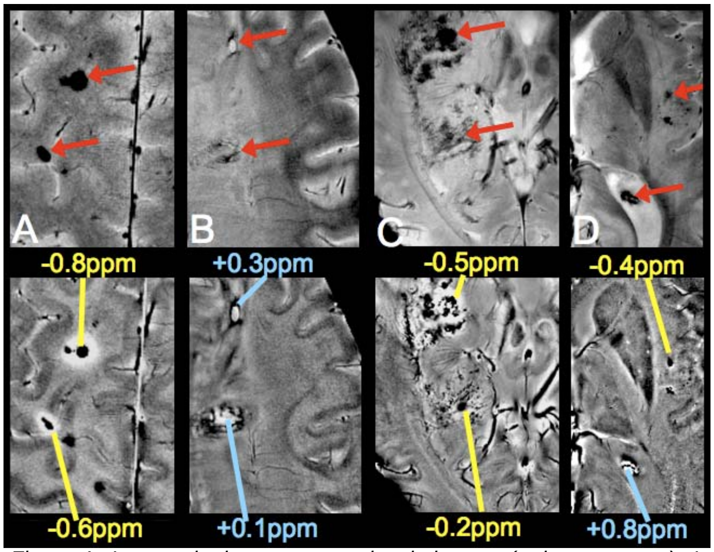

Figure 1. In magnitude, χ causes signal dropout (red arrows, top). In phase, χ can be characterized as para- (yellow) or dia-magnetic (blue) and quantified. Subjects had traumatic brain injury (A), oligo-astrocytoma (B) or glioblastoma multiforme (C-D).

Methods: *Data Acquisition* Forty-eight subjects including 25 patients with brain tumors, 8 patients with traumatic brain injury and 15 volunteers were scanned on a whole-body 7T MRI (GE Healthcare) with an 8-channel receive phased array coil (Nova Medical) and head transmitter coil with active detuning. High-resolution 2D GRE (0.35x0.35x2mm resolution, 18cm FOV, 20° flip, 3 NEX, TE/TR 11.4/250ms, 6.5 min scan) and/or 3D SPGR (0.35x0.35x1mm resolution, 20cm FOV, 10° flip, TE/TR 16/80ms, GRAPPA R = 3, 6 min scan) images were acquired. B0 field images were calculated by post-processing the phase of the complex data using in-house software [4].

***Quantification of Magnetic Susceptibility**:* The theoretical B0 field distortion for a sphere of radius 'r' is described in [5] as:

$$\text{Equation 1: } \Delta B_{0,inside} = \frac{2}{3}\Delta\chi B_0 \text{ where } \Delta B_0 = \frac{\Delta phase}{2\pi\ TE}$$

$$\text{Equation 2: } \Delta B_{z,outside} = \frac{\Delta\chi B_0 d^3}{3r^3}(3\cos^2\theta - 1)$$

The $\Delta\chi$ for suspected hemorrhages and calcifications was calculated by solving for $\Delta\chi$ in Eqn. 1.

***Magnetic Susceptibility-Based Feature Selection**:* The model ΔB field described by Eqns. 1 and 2 for a hemorrhage (r=2mm, $\Delta\chi$=-1ppm) was resampled to the scan resolution and convolved into the phase to identify where the modelled and measured B0 fields agreed (Fig. 2).

Results and Discussion: Paramagnetic features ranged from -0.13 to -1.18ppm (N=36, mean±stdev=-0.39±0.13). The paramagnetism was often seen in traumatic brain injury patients and in brain tumor patients having undergone radiation therapy (e.g. subject in Fig. 1D had undergone gamma knife radiation therapy) and likely results from iron in hemorrhages. Diamagnetic features ranged from +0.04 to +0.44ppm (N=15, mean±stdev=0.18±0.11). Diamagnetism was seen exclusively in tumors and the choroids plexus and is believed to result from calcification [6]. The $\Delta\chi$ was reproducible between three-dimensional 3T and 7T scans (Fig. 3) and between two and three-dimensional 7T scans (P>0.4, paired t-test). The appearance of χ-effects in magnitude images was highly dependent on scan parameters, did not indicate whether χ was para- or diamagnetic, and exaggerated feature size due to intravoxel dephasing outside the feature (e.g. hemorrhages in Fig. 1A). Phase was used to select for specific B0 field profiles to separate hemorrhages from veins, which were indistinguishable in the magnitude images (Fig. 2).

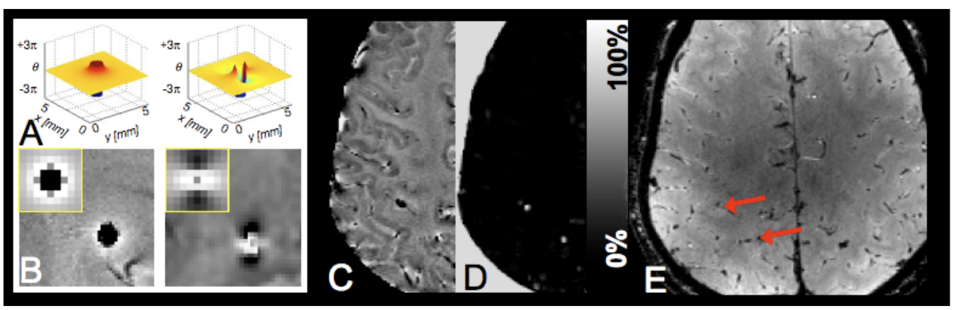

Figure 2. Sampling the model χ-effect of a hemorrhage (A, axial/sagittal on left/right) at the scan resolution created a convolution kernel (B, inset) well matched to the measured χ-effect (B). This kernel was convolved into the phase image (C) to produce an image (D) identifying which magnitude hypointensities are likely hemorrhages (arrows, E).

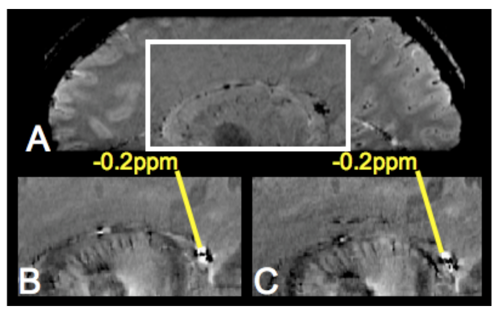

Figure 3. Sagittal 7T magnitude (A), 7T phase (B) and 3T phase (C) images of a patient with traumatic brain injury.

Conclusion: Magnetic susceptibilities were calculated from the phase of 7T GRE scans with preliminary results at 3T. This calculation was robust to scan parameters and does not require an additional scan because it uses the same data set used for magnitude imaging. The ability to reproducibly measure $\Delta\chi$ could alleviate the need for CT-based detection of calcifications and could have an enormous impact on studies of iron deposition in brain injury and neurodegenerative disorders.

References: [1] Yamada et al., (1996) Radiology 198:171-8 [2] Rauscher et al., (2005) AJNR 26:736-42 [3] Duyn et al., (2007) PNAS 104:11796-801 [4] Hammond et al., (2007) NeuroImage *In press* [5] Schenck et al., (1996) Med Phys 23:815-50 [6] Deistung et al., (2006) Z Med Phys 16:261-7

This research was funded by UC Discovery Grants (GE Healthcare) LSIT01-10107 and ITL-BIO04-10148, NIH grants ROI CA059880, P50 CA97257 and a NSF GRFP.