Rapid Multi-Orientation Susceptibility Mapping with Wave-CAIPI

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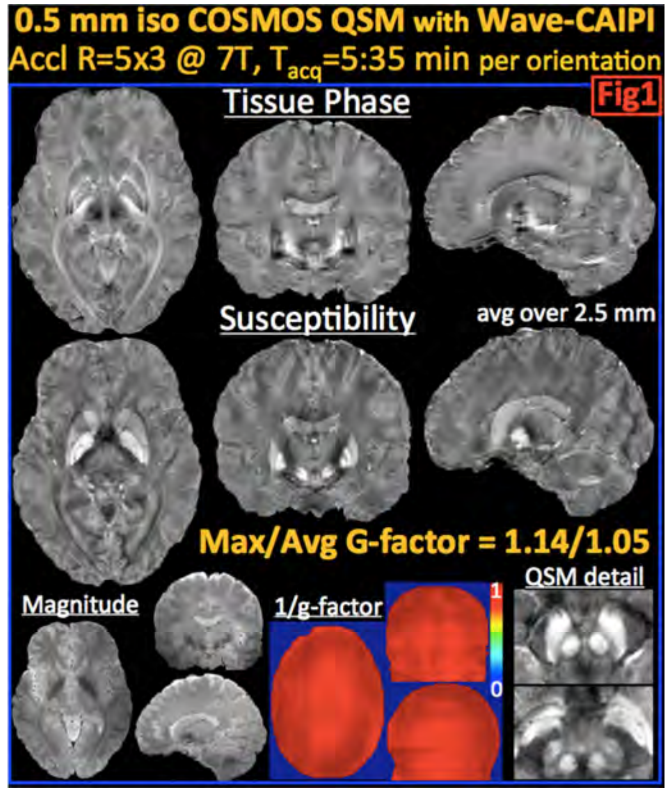
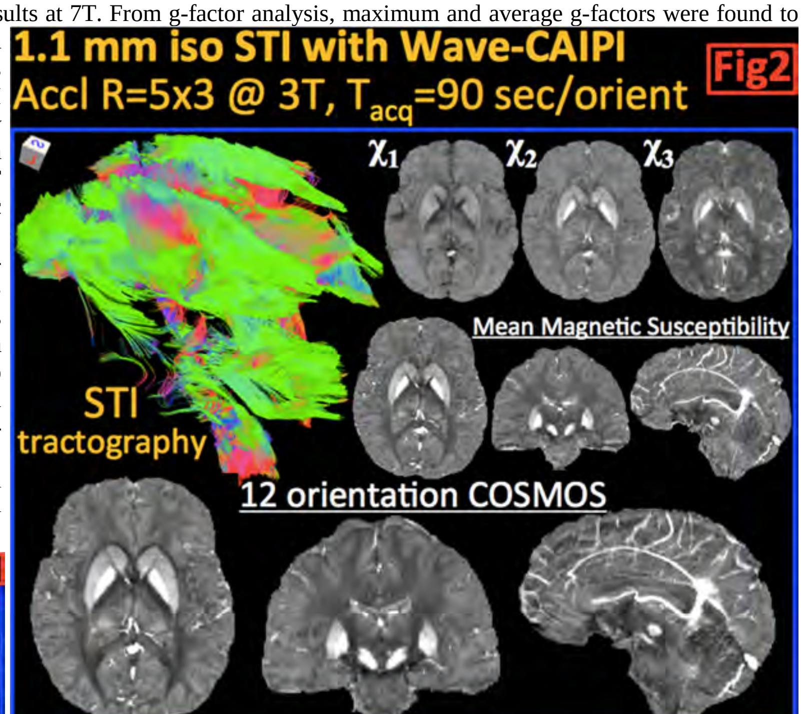
Target Audience: Physicians and scientists interested in rapid Quantitative Susceptibility Mapping (QSM) and Susceptibility Tensor Imaging (STI).

Purpose: QSM estimates the magnetic susceptibility χ that is related to subtle changes in the magnetic field ϕ through the dipole convolution $\mathbf{D}\mathcal{F}\chi = \mathcal{F}\phi$, where $\mathcal{F}$ and $\mathbf{D}$ represent discrete Fourier transform and the dipole kernel. Inversion of this ill-posed system can be achieved through spatial regularization [1], while additional datasets acquired at different head orientations can be used to improve the conditioning of this system at a cost of increased scan time. COSMOS [2] combines such multi-orientation data to mitigate dipole streaking and yields exquisite susceptibility maps, while STI [3] aims to map the orientation dependence of tissue susceptibility through a tensor model. In particular, STI requires a minimum of 6 orientations to solve the independent tensor elements in each voxel [4]. The long acquisition time makes these imaging protocols challenging for in vivo application. In this work, we substantially reduced the encoding burden of COSMOS and STI using rapid 3D-GRE imaging with recently introduced Wave-CAIPI technique [5]. With 15-fold acceleration, Wave-CAIPI permitted a **5:35 min whole-brain acquisition per orientation at 0.5 mm isotropic resolution for COSMOS, and a 90 s whole-brain acquisition per orientation at 1.1 mm isotropic resolution for STI.** Furthermore, we utilized FLEET multi-shot EPI [6] for rapid and low-distortion coil sensitivity estimation—allowing high-quality coil sensitivity estimation using head and body coil data to be acquired in only 10 s per orientation.



Methods: 3D-GRE with Wave-CAIPI traverses a highly efficient corkscrew k-space trajectory that spreads the aliasing in 3D. This scheme takes full advantage of the 3D variation in the coil sensitivities, and enables highly accelerated imaging with low artifact levels and negligible noise amplification (g-factor) penalties. **COSMOS:** A healthy volunteer was scanned at 7T to acquire 0.5 mm isotropic data with 3 orientations (neutral, 7° left, 13° right) with a large FOV (255×255×180 mm) to accommodate rotation using a custom 32 channel coil. R=5×3 acceleration lead to T_{acq}=5:35 min with 480×480×360 matrix at TE/TR = 19.5/29 ms and BW = 100 Hz/px. The volumes were registered using FSL FLIRT and tissue phase images were obtained with Laplacian unwrapping [7] and V-SHARP filtering [7-8]. LSQR algorithm was employed for COSMOS reconstruction to solve $min_\chi \sum_i \|\mathbf{W}(\mathcal{F}^{-1}\mathbf{D}_i\mathcal{F}\chi - \phi_i)\|_2^2 + \lambda\|\chi\|_2^2$, where $\mathbf{W}$ is derived from the magnitude for noise weighting, and i is the orientation index. As the tight-fitting custom 32-channel helmet coil restricts head motion, setting λ=0.05 helped mitigate residual streaking. **STI:** A healthy volunteer was imaged at 3T to acquire 1.1 mm isotropic data at 12 orientations (max rotation: 25°) using the vendor's 32 channel coil. With R=5×3, T_{acq} was 90 sec per orientation with 240×240×168 matrix at TE/TR = 25/35 ms and BW = 100 Hz/px. Tensor fitting was performed with LSQR by solving $min_{\bar{\bar{\chi}}} \sum_i \|(1/3\mathrm{H}_i^T\bar{\bar{\chi}}\mathrm{H}_i - k\cdot\mathrm{H}_i(k^T\bar{\bar{\chi}}\mathrm{H}_i)/k^2) - \mathcal{F}\phi_i\|_2^2$, where H_i is the unit field vector in the i^{th} subject frame and $\bar{\bar{\chi}}$ is the tensor in k-space. Tractography was performed in DTK and visualized in TrackVis.

Results: Fig1: Phase, COSMOS susceptibility, and magnitude results at 7T. From g-factor analysis, maximum and average g-factors were found to be $\mathbf{g_{max}/g_{avg}}$ **= 1.14/1.05**, indicating very low noise amplification in the parallel imaging reconstruction. QSM detail sub-figure shows exquisite depiction of deep gray matter structures. **Fig2:** STI tracts, eigenvalues of the tensor, Mean Magnetic Susceptibility (MMS, mean of the eigenvalues) and the COSMOS solution from 12 orientations are presented from the 3T data. **Fig3**: EPI-FLEET enables rapid head and body coil acquisitions at 3.9 mm isotropic resolution for coil sensitivity estimation in 10 sec.



Discussion: Wave-CAIPI attains high quality reconstruction at 15-fold acceleration to facilitate fast acquisition of extremely time-consuming COSMOS and STI protocols. This technique reveals exquisite cortical contrast and provides detailed depiction of iron rich nuclei at 7T, as well as enabling rapid acquisition of in vivo STI at 3T. Combined with fast coil sensitivity mapping and shimming for each orientation, Wave-CAIPI permits 12-orientation STI at 1.1 mm resolution to be completed in 25 min.

References: [1] De Rochefort L, MRM'10; [2] Liu T, MRM'09; [3] Liu C, MRM'10; [4] Li W, NIMG'12; [5] Bilgic B, MRM'14; [6] Polimeni JR, ISMRM'13; [7] Wu B, MRM'12; [8] Schweser F, NIMG'11