Rapid Acquisition for Multi-Orientation QSM

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INTRODUCTION: Quantitative Susceptibility Mapping (QSM) involves the solution of the system $\mathbf{D}\mathcal{F}\chi = \mathcal{F}\phi$ that relates the susceptibility map χ to the tissue phase ϕ derived from a gradient echo (GRE) experiment. In this relation, $\mathcal{F}$ is the 3D DFT operator, and $\mathbf{D} = 1/3 - k_z^2/k^2$ is the kernel that undersamples the frequency content of χ on the surface $3k_z^2 = k^2$. The solution of this ill-conditioned system is facilitated by regularized inversion that imposes smoothness or sparsity constraints [1-3]. Alternatively, additional GRE volumes can be acquired while the subject's head is rotated to make an angle θ relative to the main field direction, in which case the susceptibility kernel is modified as $\mathbf{D}(\theta) = 1/3 - (k_z\cos\theta + k_y\sin\theta)^2/k^2$. As this causes the undersampled surface to vary as a function of θ, a well-conditioned system can be obtained when (at least) 3 orientations are sampled [4-6]. Multi-orientation QSM yields exquisite susceptibility maps and obviates the need for regularization that may introduce over-smoothing [6], but suffers from increased encoding burden. We introduce efficient acquisition strategies, 3D-GRE with Wave-CAIPI [7] and 3D-EPI [8], which mitigate this issue to facilitate clinical application of multi-orientation QSM. **Wave-CAIPI enables a whole-brain 3D-GRE acquisition at 1mm isotropic resolution in 3:25 min with 9-fold acceleration, while 3D-EPI acquisition is completed in 1:05 min at the same resolution with 4 averages.**

METHODS: 3D-GRE with Wave-CAIPI involves playing sinusoidal G_y and G_z gradients during the readout of each phase encoding line, which results in a highly efficient corkscrew k-space trajectory that spreads the aliasing evenly in 3D. Since this scheme takes full advantage of the variation in the 3D coil sensitivities, it enables highly accelerated 3D imaging with low artifact and negligible noise amplification (g-factor) penalties. We represent the non-Cartesian trajectory as convolution with a point spread function (psf) in Cartesian space. This can be expressed as $\text{wave}_{y,z} = \text{psf}_{y,z} \otimes \text{img}_{y,z}$, where $\text{wave}_{y,z}$ is the image row at location (y, z) acquired with Wave gradients, $\text{img}_{y,z}$ is the underlying magnetization, and $\text{psf}_{y,z}$ is the position-dependent psf that explains the voxel spreading effect in readout direction. In the presence of undersampling, the voxel spreading increases the distance between aliasing voxels, thereby vastly improving g-factor and parallel imaging capability. The Wave equation is augmented with coil sensitivities to unalias the collapsed voxels. A healthy volunteer was scanned at 3T with FOV=240×240×192, TR/TE=40/30 ms, 1 mm^3 resolution, R=3×3 acceleration, and 3 orientations were sampled (left, right, back) with total acquisition time of 10.3 minutes.

Wave-CAIPI QSM & Phase from 3 head orientations
R=3x3 @ 3 Tesla, 1 mm iso, T_{acq}=10.3min

Fig1 Tissue Phase: mean over 3 orientations

Susceptibility: max intensity projection over 3mm slabs

3D-EPI: follows an EPI trajectory for in-plane sampling, with phase encoding in the partition axis. This results in an efficient encoding strategy with the SNR benefit of 3D signal averaging. A healthy volunteer was scanned at 3T with FOV=230×230×176, TR/TE=69/30 ms, 1 mm^3 resolution, 4 averages, and 3 rotations were sampled (neutral, front & left, back & right) with total acquisition time of 3.3 minutes. 3-fold in-plane acceleration was employed to reduce distortion.

Data processing: Phase data was processed with Laplacian unwrapping [3] and V-SHARP filtering for background removal [3,5]. Magnitude images from Wave-CAIPI acquisition were registered onto the neutral orientation with FSL-FLIRT, whereas nonlinear registration using FNIRT was employed to account for distortion in the 3D-EPI dataset. The resulting rotation matrices were used to derive orientation information required for susceptibility kernel creation.
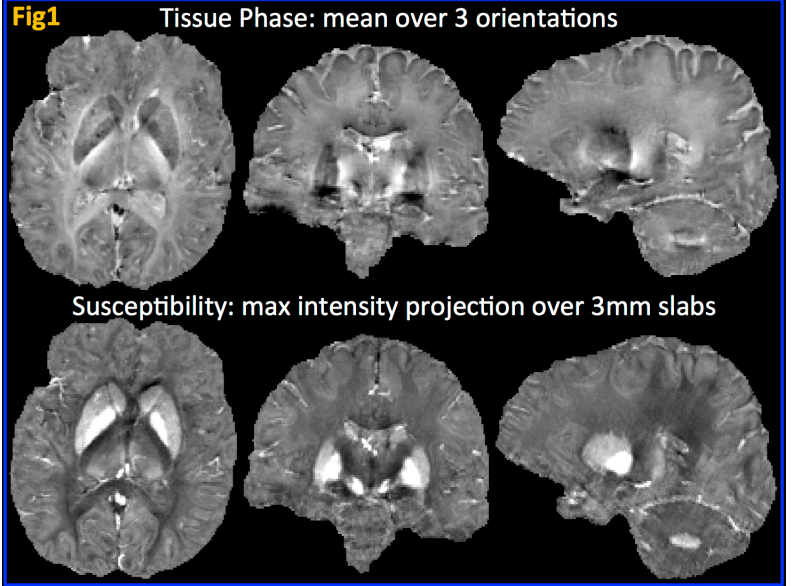
Closed-form COSMOS: The susceptibility map that matches the multi-orientation phase data was found by solving $min\sum_i\|\mathbf{D}_i\mathcal{F}\chi - \mathcal{F}\phi_i\|_2^2$, where $\mathbf{D}_i$ is the kernel and ϕ_i is the tissue phase at orientation i. This admits a closed-form solution $\chi = \mathcal{F}^{-1}(\sum_i \mathbf{D}_i^2)^{-1}\sum_i \mathbf{D}_i^T\mathcal{F}\phi_i$, where all matrix operations are simple point-wise multiplications and reconstruction takes a few seconds. This fast processing is made possible by omitting the noise weighting term in the COSMOS formulation [4].

RESULTS: Fig.1 shows phase and QSM from Wave-CAIPI accelerated 3D-GRE with 3 orientations. The maximum and average g-factors for the 3D volume in the back orientation were **1.03** and **1.01**, indicating near-perfect parallel imaging reconstruction. **Fig.2** depicts detailed phase and susceptibility maps using 3D-EPI with 3 orientations.

DISCUSSIONS AND CONCLUSIONS: The presented efficient protocols may facilitate multi-orientation QSM acquisition, which preserves exquisite cortical contrast and does not suffer from smoothing effect of regularized reconstruction. While 3D-EPI is more efficient than the Wave-CAIPI accelerated 3D-GRE, it is limited by geometric distortion, which complicates registration and requires time consuming nonlinear warping. As such, image distortion and encoding efficiency can be traded off to choose between the two proposed methods for a specific application. Since the current Wave-CAIPI protocol uses a large FOV to accommodate different head orientations, acquired k-space is inherently oversampled. The perfect g-factor obtained at 9-fold undersampling warrants further acceleration, e.g. R=4×4, which will enable a 2-minute whole-brain acquisition.

3D-EPI QSM & Phase from 3 orient.
$R_{inplane}$=3 @ 3T, 1 mm iso, T_{acq}=3.3min

Fig2 Avg Tissue Phase

Susceptibility

max intensity projection over 3mm

REFERENCES: [1] De Rochefort L, MRM'10; [2] Liu J, NIMG'12; [3] Wu B, MRM'12; [4] Liu T, MRM'09; [5] Schweser F, NIMG'11; [6] Wharton S, NIMG'10; [7] Bilgic B, ISMRM'14; [8] Poser BA, NIMG'10; [9] Breuer FA, MRM'06; [10] Pruessmann KP, MRM'01.