Open-Source Self-navigated Multi-Echo GRE Acquisition for R_2* and QSM mapping using Pulseq and Model-Based Reconstruction

Xiaoqing Wang[1], Berkin Bilgic[1], Daniel Gallichan[2], Kwok-Shing Chan[3], José P. Marques[3]

1 Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, Charlestown, Massachusetts, USA. 2 Cardiff University Brain Research Imaging Centre, Cardiff, UK. 3 Donders Institute for Brain, Cognition and Behavior, Radboud University, Nijmegen, The Netherlands

Target audience: Researchers interested in open-source sequence development and reconstruction algorithms, particularly for efficient quantitative imaging.

Introduction: There are various ongoing projects aiming to harmonize protocols across vendors. In the context of QSM, the current recommendation is a 3D multi-echo gradient echo (3DME-GRE) acquired axially to reduce scan time and achieve 1 mm iso. resolution while using coils that might not be state of the art [1]. This requires 6 min, which remains long for research/clinical applications, and does not account for respiration related B_0 fluctuations known to degrade R_2* and susceptibility maps. Further, it is not possible to know how similar the implementations are between different vendors e.g. in terms of gradient/RF spoiling, excitation profiles and image reconstruction. We propose an open-source sequence and reconstruction algorithms for rapid acquisition and harmonization of R_2* mapping and QSM. This is implemented in Pulseq [1], where different sampling patterns are used across echoes to provide complementary information and facilitate the proposed MOdel BAsed (MOBA) reconstruction, which estimates M_0, R_2* and frequency maps using nonlinear optimization.

Methods: Pulseq was used to implement CAIPI patterns that are shifted across-echo times (Fig. 1a,b). A 1D navigator was added as part of the gradient crusher (Fig.1a) which allowed for B_0 correction. Motion navigators inserted in the sequence permit robust estimation of motion parameters with time frames of ~13 sec (not shown), and may lend themselves to retrospective motion correction. Sequence/reconstruction code: github.com/berkinbilgic/pulseq_qsm

Acquisition: was performed on a 3T Prisma equipped with a 32-channel coil using: R=9-fold acceleration with [R_y, R_z, $Caipi_{z\text{-shift}}$, $Caipi_{z\text{-echo-shift}}$] = [1,9,3,2], TR=35ms, $TE_1/\Delta TE/TE_6$=3/5/28ms, flip angle=15°, sagittal acquisition, FOV=[256,198,225] mm, 1mm isotropic, central [27 ,36] PE_y and PE_z lines were fully sampled and used for both motion correction and image reconstruction. Acquisition time=4mins.

One subject was scanned twice: either breathing normally or taking deep breaths to induce motion and additional B_0 artifacts. B_0 correction was implemented by fitting a first order polynomial to the phase of the navigator, and applying that correction across all echo readouts.

MOdel-BAsed Reconstruction (MOBA): Different CAIPI sampling patterns across the echoes and GRE signal model were exploited by solving [4]: $x = (M_0, R_2^*, f) = argmin_x \sum_{TE} \left\| PFC \cdot M_0 \cdot e^{-TE\cdot R_2^* + i2\pi\cdot TE\cdot f} - Y \right\|_2^2 + R(x)$. While a joint L1-Wavelet sparsity constraint was applied to M_0 and R_2^* maps to improve quantitative accuracy, Sobolev regularization was adopted for the frequency map f to enforce smoothness. MOBA was implemented on BART [3] using GPUs.

Results: Fig.1c shows that the B_0 correction that has a clear impact particularly on the later echoes in deep breathing. Fig.2 depicts R_2*, M_0 and QSM estimates obtained from SENSE at R=9. SEPIA's [5] implementation of LP-CNN [6] was used for dipole inversion. MPPCA denoising [7] was applied on the complex SENSE volumes across the echoes to denoise the data prior to parameter estimation. Fig.3 shows an exemplar slice from the MOBA at R=9, and compares this to SENSE results. Improved SNR is observed in the R_2* and M_0 maps. Tissue phase was obtained by V-SHARP background removal [8] applied directly on the frequency map f estimate, without additional unwrapping.

Conclusion: As R_2* mapping quality is typically plagued by short TEs used, B_0 navigation permits longer TEs, while MOBA combined with controlled aliased patterns across echos allows higher acceleration factors. Future work will explore accelerated acquisitions in clinical RF setups with 12 and 16 channels using wave encoding [9], water-fat separated MOBA and retrospective motion correction.

References: [1] QMR Lucca 2022 Workshop. [2] KJ Layton, MRM'17. [3] M Uecker, ISMRM'16. [4] Z Tan, MRM'22. [5] KS Chan, NIMG'21. [6] KW Lai, MICCAI'20. [7] J Veraart NIMG'16. [8] B Wu, MRM'11. [9] B Bilgic, MRM'15.

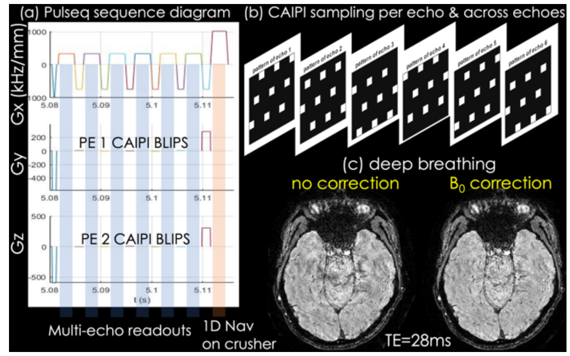

Fig1. (a) Pulseq implementation includes CAIPI blips and a navigator readout during the crusher. (b) Different CAIPI patterns across echoes provide complementary information for joint reconstruction. (c) Navigator permits B_0 correction as demonstrated in deep breathing.

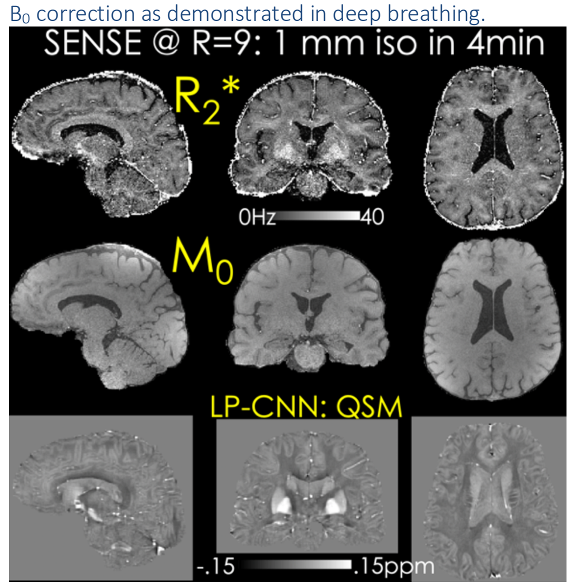

Fig2. SENSE at R=9 leads to artifact-free R_2* and M_0 maps. High-quality QSM is obtained from the multi-echo phase using deep-learning aided reconstruction in SEPIA toolbox.

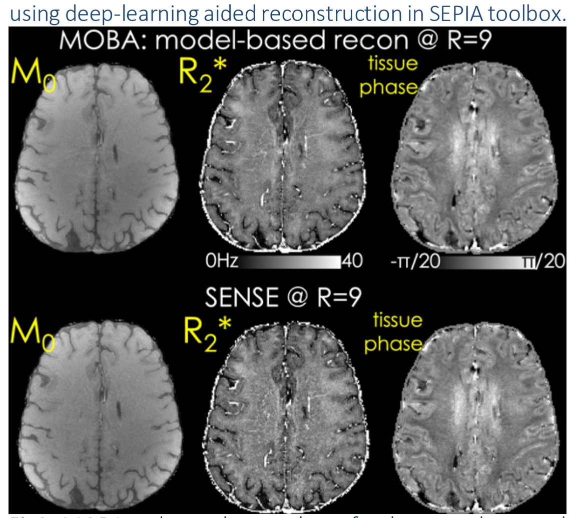

Fig3. MOBA reduces the number of unknowns that need to be estimated from ME-GRE data and exploits complementary CAIPI sampling patterns across echoes to provide parameter maps with higher SNR.