

High-resolution whole-brain multi-parameter mapping at 7 Tesla with interleaved fly-back 3D-EPI and universal pTX pulses

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Synopsis

We present a versatile high-resolution whole-brain multiparametric/susceptibility mapping protocol at 7T, introducing interleaved fly-back skipped-CAIPI 3D-EPI. To overcome the impeding limitations of B_1^+ inhomogeneity, universal pTX pulses for excitation and magnetization transfer saturation are employed. Within 17 minutes scan time, 0.6mm isotropic whole-brain MT-/PD-/T1-weighted magnitude and phase images at four echo times and corresponding quantitative parameter maps are obtained. Supplementary output, like SWI and MPRAGE-like images can be generated as well. Scan efficiency is high and geometric distortions are negligible. Optionally, the interleaved fly-back acquisition allows a separate analysis of two monopolar readout images.

Summary of Main Findings

Whole-brain quantitative multi-parameter mapping at 0.6mm isotropic resolution is feasible at 7T within 17 minutes scan time by combining a novel interleaved fly-back readout for skipped-CAIPI multi-echo 3D-EPI with universal pTX pulses.

Abstract

Introduction

Combining multiparametric mapping (MPM)¹ with scan-efficient segmented 3D-EPI has been shown to provide reliable quantitative parameter maps at 1mm isotropic resolution within only 3 minutes at 3T.² At 7T, results were yet compromised mainly by inhomogeneous B_1^+ . In this study, targeting the cerebellum, we tackle those problems by using universal parallel transmit (pTX) excitation³ and magnetization transfer (MT) saturation pulses. At the same time, by introducing a scan-efficient interleaved fly-back EPI readout, sensitivity to off-resonance artifacts and other scan imperfections is reduced. The two simultaneously acquired monopolar magnitude and phase images per contrast can either be analyzed separately or averaged before analysis.

Methods

A custom segmented multi-echo 3D-EPI sequence with skipped-CAIPI sampling⁴ is used for all images acquired with a Siemens MAGNETOM 7TPlus system (Siemens, Healthineers) with a 32Rx/8Tx head coil. Three major novelties have been implemented:

- 1) As depicted in Fig. 1, two monopolar multi-echo images, $S^\downarrow$ and $S^\uparrow$, are acquired simultaneously by combining an interleaved fly-back EPI readout with skipped-CAIPI sampling ($3 \times 2_{z1}$, segmentation factor 23, partial Fourier 6/8, EPI factor 4, FOV=216x216x192mm³, 0.6mm isotropic resolution, TE=[5.3, 12.2, 19.1, 26.0]ms, TR/nominal FA/TA for MTw, PDw, T1w: 48ms/6°/6:08min, 34.5ms/4°/4:28min, 34.5ms/25°/4:28min). Remaining phase inconsistencies of $S^\uparrow$ compared to $S^\downarrow$, can be corrected retrospectively in image space as shown in Fig. 2 ($S_{rPC}^\uparrow$).
- 2) Either simple CP-mode water excitation⁵ or pTX interleaved binomial 5-kT-points excitation⁶ is performed (“X” in Fig. 1A). For MT saturation (“S” in Fig. 1A), either a 10ms CP-mode Gaussian pulse (nominal FA=200°), or 10ms pTX saturation based on pulse design for homogeneity (PUSH)⁷ is performed.
- 3) To avoid time-consuming, on-line pTX pulse computations, universal excitation and MT saturation pTX pulses³ – optimized for the whole-brain, based on a pre-acquired B_1^+ and B_0 data base of 10 subjects – are used. The latter homogenizes the root-mean-squared B_1^+ .

Parallel image reconstruction and coil combination are done online using a virtual reference coil.⁸ The total acquisition time of a complete MPM data set is TA=15:04min. Two complete MPM data sets using a) only CP pulses and b) only UP pulses were acquired on a volunteer, who was not part of the previous B_1^+ / B_0 data base. For MPM analysis, B_1^+ maps of UP and CP excitations were additionally acquired using actual flip angle imaging (AFI)⁹

(4mm iso, FA=20°, TR1/TR2=20ms/100ms, TA=1:50min) and computed from a channel-wise 3DREAM scan¹⁰ (4mm iso, FA=60°, TA=0:29min), respectively. Based on the magnitude and phase of the dual-polarity average of $S^\downarrow$ and $S_{r,PC}^\uparrow$, multi-parameter maps are calculated with the hMRI toolbox¹¹ and susceptibility maps are computed separately for each contrast using ROMEO¹² and QSMxT.¹³

Results

Figure 3 shows dual-polarity-averaged magnitudes for all contrasts at all TEs using CP pulses and UPs. The multi-parameter maps in Fig. 4 show clear deficits when using CP pulses, in particular R_1 and MT_{sat} in the cerebellum. The UP data achieve good results throughout the brain. Only MT_{sat} still shows some degree of inhomogeneity. Fig. 5 shows supplementary example output generated from the same data, e.g. MPRAGE-like and susceptibility-weighted images (SWI).

Discussion

The weighted magnitude images (Fig. 3) already show that the UPs clearly gain signal and contrast compared to the CP pulses. Accordingly, the resulting parameter maps of Fig. 4 are largely improved in the critical area of the cerebellum. Since only the MT_{sat} shows residual inhomogeneities, despite its clear improvement over the CP-mode maps, it seems that further improving the PUSH MT saturation pulses may be required.

The interleaved binomial kT-point excitation pulses homogenize the excitation sufficiently. However, comparing the UP to the CP R_1 maps, one can appreciate that particularly white matter R_1 is decreased with the UPs. This is likely due to a different amount of accidental MT saturation, particularly in the T1w image: the 1ms long CP pulses are more narrow-banded and thus result in less unwanted MT saturation than usual in MPM;² the UP pulses, on the other hand, consisting of several very short subpulses, were not optimized to reduce off-resonance saturation. Future investigations will incorporate off-resonance energy constraints in the UP excitation optimization.

Finally, the susceptibility maps of Fig. 4 and the supplementary output of Fig. 5 demonstrate that the rich whole-brain data with different T_2^* -weighting (cf. Fig. 3) – which itself is an important diagnostic contrast^{14,15} – can replace further acquisitions, like QSM and SWI. Even a conventional MPRAGE scan may be skipped, however further validation and optimization is required.

Since the complete 17 minute protocol actually consists of three self-contained MTw/PDw/T1w imaging blocks (about 6 and two times 4.5 minutes) and a B_1^+ map, the protocol is relatively motion-robust, while inter-scan co-registration is done routinely within the MPM framework. Adding further gradient-echo-based contrasts, e.g. potentially for high-resolution phase-based T2 imaging,¹⁶ is straight-forward and may be promising.

Conclusion

Within 15 minutes of scan time using skipped-CAIPI multi-echo 3D-EPI at 7T, whole-brain multi-parameter mapping at 0.6mm isotropic resolution is feasible. The novel interleaved fly-back readout minimizes segmentation artifacts. Importantly also, the tailored universal pTX pulses successfully solved major previous B_1^+ problems for quantitative imaging. Aside from the native contrasts and quantitative parameter maps, further contrasts that are relevant for clinical and research applications can potentially be generated, and thus acquisition time may be saved.

Acknowledgments

The first author wants to thank Simon Robinson and Jin Jin for helpful discussions and advice on appropriate on-line coil combination.

This work received financial support from the European Union Horizon 2020 Research and Innovation program under grant agreement 885876 (AROMA). Furthermore, the work is part of the SCAIFIELD project under the aegis of JPND, supported through the following funding organizations: Belgium, The Fund for Scientific Research (F.R.S.-FNRS); Germany, Federal Ministry of Education and Research (BMBF; funding codes 01ED2109A/B); Norway, The Research Council of Norway (RCN); Turkey, Scientific and Technological Research Council of Turkey, TÜBİTAK.

Submission Categories

- Primary:
 - Acquisition & Analysis
 - * Quantitative Imaging
 - * General Keyword: High-Field MRI
 - * Other General Keywords: MPM, QSM, 3D-EPI
- Secondary:
 - Contrast Mechanisms
 - * Multi-Contrast
 - * General Keyword: Parallel Transmit & Multiband
 - * Other General Keywords: MPM, QSM, 3D-EPI

Final Decision

The abstract has been selected for presentation in the "in-person Oral Scientific session: *Advances in Quantitative Neuroimaging*."

- Day/Date: Monday, 05 June 2023
- Session Time: 16:00

Figures

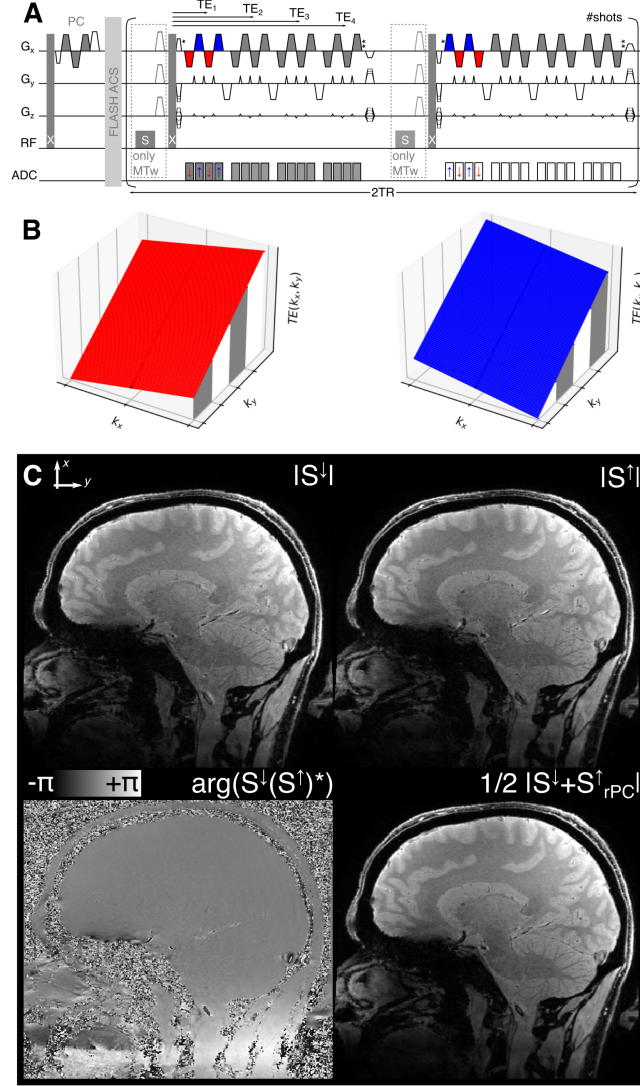


Fig. 1 Interleaved fly-back 3D-EPI (A). The echoes of two consecutive shots (identical up to inverted readout polarity), are assigned to two monopolar $\downarrow$ and $\uparrow$ k-spaces in an alternating fashion (B). With adequate echo time shifts ($^*/^{**}$), TE becomes continuous for all (k_x, k_y) in both k-spaces, preventing segmentation image artifacts even in the spine (C). Geometric distortions and phase differences between $S^\downarrow$ and $S^\uparrow$ images are negligible within the brain. S : CP/UP MT-saturation; X : CP/UP excitation; $\#shots \sim$ undersampled k_y and k_z samples divided by EPI factor.

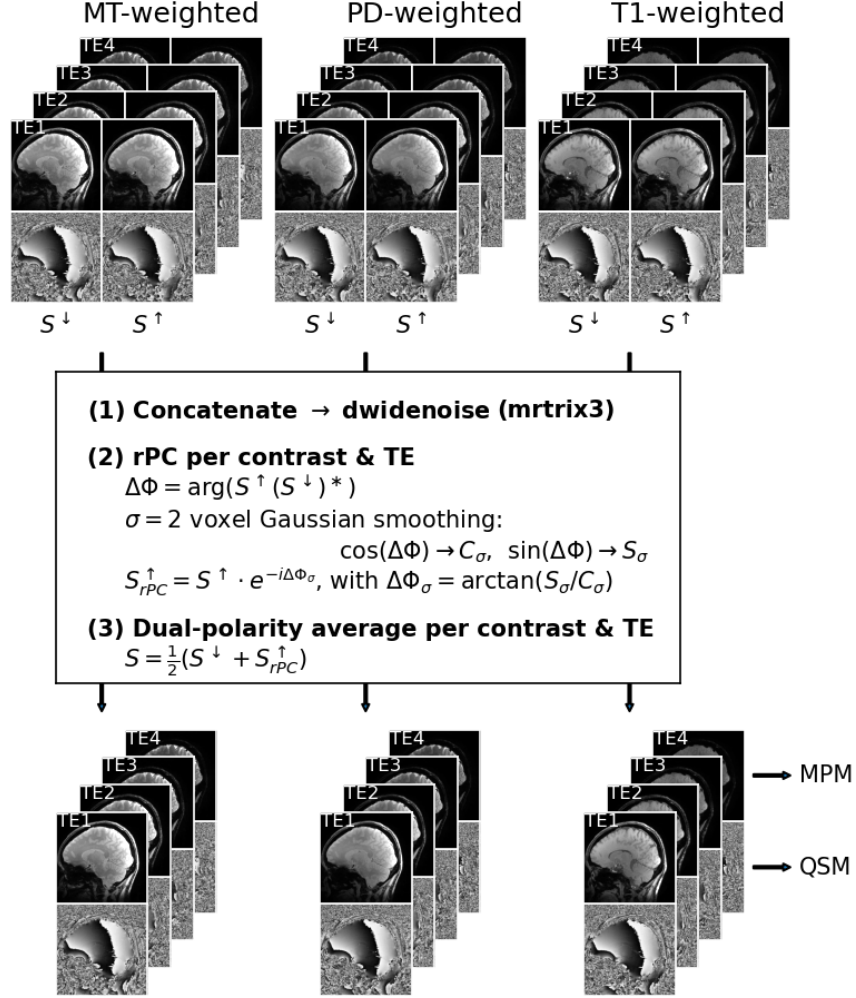


Fig. 2 Schematic of MPM + QSM data acquisition and preprocessing. For retrospective phase correction (rPC), the phase of $S^\uparrow$ is rewound to the phase of $S^\downarrow$. Smoothing of the relatively flat phase difference $\Delta\Phi$ (cf. Fig. 1C) assures that $\arg(S_{rPC}^\uparrow)$ only becomes identical to $\arg(S^\downarrow)$ up to noise, such that dual-polarity averaging can maximize SNR.

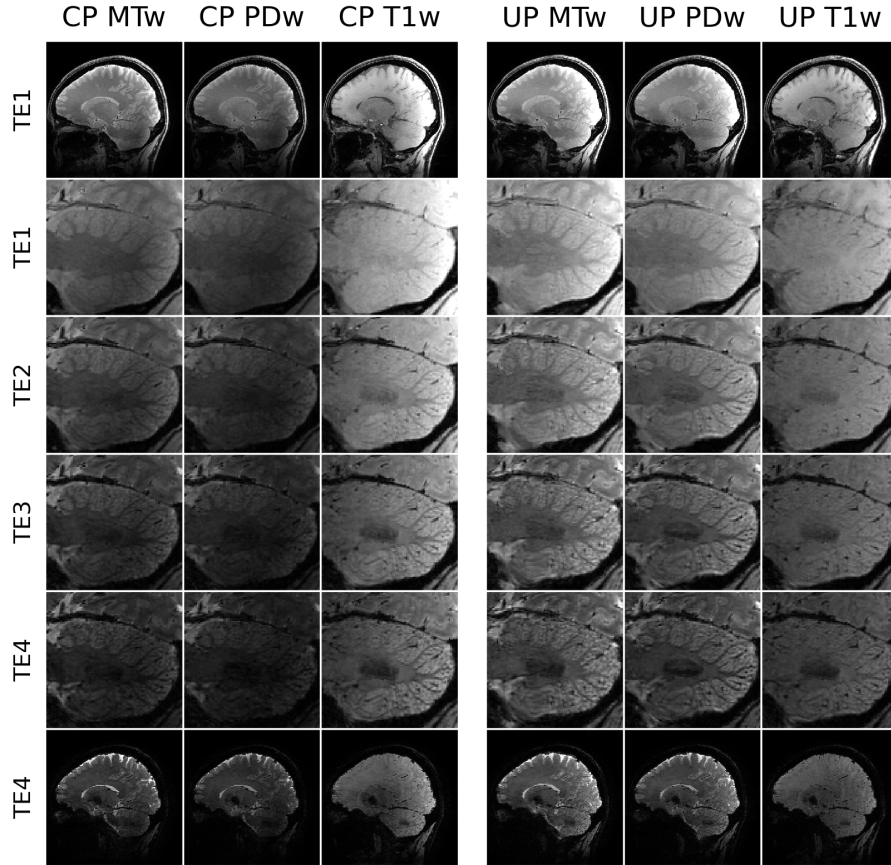


Fig. 3 Sagittal example views of all dual-polarity-averaged MPM magnitude contrasts for CP-mode excitation/MT saturation (left) and UP excitation/MT saturation (right). In particular the MTw and PDw scans (small FA $\sim B_1^+$) showcase the lack of B_1^+ in the CP-mode images. The CP-mode T1w images in fact show a PD-weighted contrast in the cerebellum. With UP excitation, the B_1^+ excitation problem is greatly mitigated.

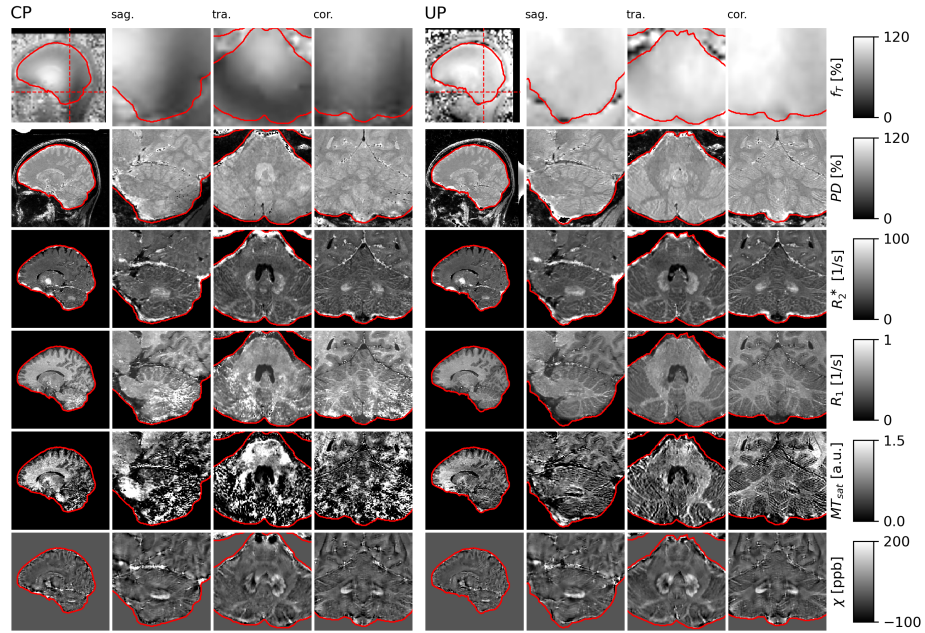


Fig. 4 Sagittal, transverse and coronal views of quantitative PD, R_1 , R_2^* , MT_{sat} and PDw susceptibility maps obtained using CP-mode (left) and universal pulses (right) with the proposed sequence protocol (cerebellum zoom factor 2.4). Top row: transmit correction map f_T (flip angle map relative to nominal flip angle) used for the MPM analysis. Dashed red lines indicate the transverse and coronal slices of the other views. The solid red line indicates the overall brain outline.

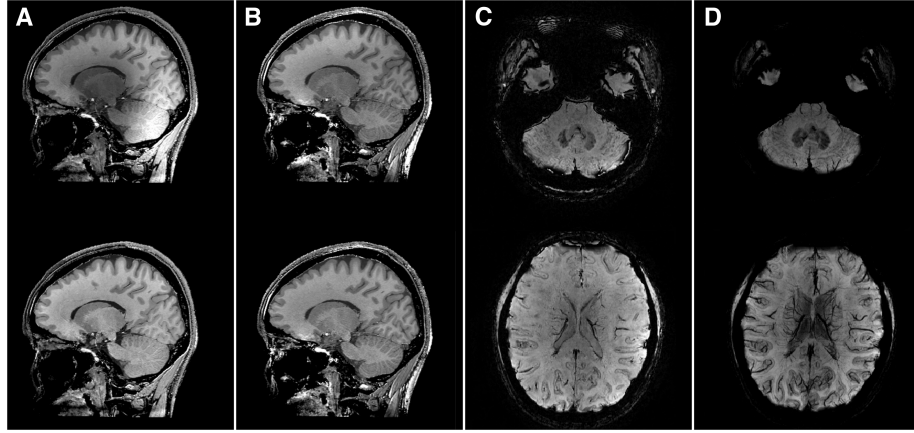


Fig. 5 Supplementary output generated from the MPM+QSM data. MPRAGE-like contrast without (top) and with bias field correction (bottom) obtained as $(|S_{T1w}| - 200) / (|S_{PDw}| + |S_{MTw}| + 400)$ from CP data (A) and UP data (B). Note the complete lack of WM/GM contrast in the cerebellum using CP data. The UP result automatically comes relatively free of receive bias. Example susceptibility-weighted images (C) generated from the UP T1w data at TE3=19.1ms and corresponding minimum-intensity projections along a 7mm slab (D).

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