Optimization of fast Quantitative Multiparameter Mapping (MPM) at 7T using parallel transmission

Difei Wang[1], Rüdiger Stirnberg[1], Eberhard Pracht[1], Tony Stöcker[1,2]

1 German Center for Neurodegenerative Diseases (DZNE), Bonn, Germany

2 Department of Physics and Astronomy, University of Bonn, Bonn, Germany

Synopsis

We propose a fast MPM protocol at 7T using skipped-CAIPI 3D-EPI with simple PTx water-excitation based on 3 k_T-points. By comparison to corresponding CP mode scans, the 3 k_T-points excitation mainly improves the $B1^+$ field homogeneity in the Cerebellum. Using MPM $B1^+$ field correction, this simple improvement is sufficient to achieve good and homogeneous T_1, PD and T_2* estimates throughout the brain. However, the lack of MT homogenization still results in the inadequate MT_{sat} CNR. By combining MPM with EPI and PTx, we obtained quantitative whole-brain parameter maps of high quality, except for Cerebellar MT_{sat} within 3 minutes scan time.

Summary of Main Findings

Fast MPM is achieved at 7T using 3D-EPI with PTx pulses to reduce $B1^+$ field variation. The weighted PTx images are more homogeneous in the Cerebellum. The residual variations are corrected by $B1^+$ map in the MPM framework, resulting in high-quality parameter maps.

Introduction

Recently, following a fast multiparameter mapping (MPM) implementation at 3T (1), a corresponding protocol at 7T was proposed (2) using 3D-EPI with segmented CAIPIRINHA (skipped-CAIPI) sampling (3). In this work we propose to overcome a critical part of the remaining challenges of the previous work by utilizing water-selective k_T-points pulses (4).

Methods

All data were acquired on a Siemens MAGNETOM 7T Plus scanner using 32-channel head receive coil and 8-channel transmit array. One set of 3D-EPI T_1w, PDw and MTw images was acquired at 4 equidistant TEs between 4.64 and 19.64 ms at 1 mm isotropic resolution. A $20.2x2_{z1}$ skipped-CAIPI sampling was employed, resulting in an EPI factor of 4. Repetition time/flip angle were chosen as follows: 27 ms/3° for PDw, 27 ms/20° for T_1w and 45 ms/4° for MTw. A single rectangular RF pulse with long duration (1.0ms) was used for simple fat suppression using traditional circularly polarized excitation (5). The corresponding PTx scans were acquired

using 3 k_T-points RF excitation pulses with the same nominal flip angles. Each sub-pulse also has 1.0 ms duration for fat suppression as previously used for fMRI (4). Both CP and PTx MTw scans used the same Gaussian-shaped CP mode RF pulse applied prior to each excitation.

In order to keep the specific absorption rate (SAR) within the safety limits, the nominal MT flip angle had to be reduced from 320° in the CP mode MTw scan to 260° in the PTx-MTw scan. A second PTx-MTw scan was acquired with prolonged TR (74 ms) to achieve the same 320° nominal MT flip angle within SAR limits. The total acquisition time of the CP mode MPM scans and the PTx MPM scans (incl. both MTw scans) were 2:59 and 5:05, respectively. All imaging parameters are summarized in Tab.1.

Two B1 maps were acquired using the same CP mode and PTx pulses by modifying the 3D-EPI sequence to include two subsequent TRs according to the Actual Flip angle Imaging (AFI) method (6) with TR_2 = 100 ms/TR_1 = 20 ms, nominal flip angle = 50°, 5mm isotropic resolution, 4.2x2$_{z1}$ skipped-CAIPI sampling (EPI factor 5), TA = 0:10 for both.

All parameter maps are calculated with the hMRI toolbox (7).

Results

Fig.1 shows representative sagittal, coronal and axial slices of all scans at TE = 4.64 ms. In the PDw images, it can be observed that PTx excitation is more homogeneous in the Cerebellum (red arrow). In the T_1w images, this shows as an improved WM/GM contrast compared to the CP scan. However the PTx scans have slightly reduced signals above the sphenoid sinus (blue arrow). The different nominal saturation flip angles and TRs resulted in nearly 100% SAR estimation (in "1st level safety mode"). Fig.2 demonstrates the example sagittal slices of distortion corrected MTw image along with MTw scan with uncorrected AP and PA phase encoding. The difference is neglectable, therefore the remaining results are presented for AP phase encoding only. Fig.3 shows the quantitative parameter maps acquired using CP mode and PTx pulses together with the corresponding $B1^+$ scale maps. Fig.4 shows the (a) MTsat histogram and bar plots of (b) T_2^*, (c) PD^*, (d) T_1 estimates in different regions of interest (ROI) from CP and PTx scans (MTw TR = 45ms). The smaller error bars of T1 in WM and GM in PTx scans show that the transmit field inhomogeneities could be compensated for in the parameter maps. However, low MT saturation flip angles of all three scans are not adequate to provide enough MT contrast: the low CNR is not sufficient to create clearly separated modes in histogram (8). In some ROIs, the T_1 estimates of PTx scans are slightly higher than that of CP scans and the literature values.

Discussion

Our study shows that MPM protocol using skipped-CAIPI 3D-EPI with PTx pulses is feasible. The simplest form of water-selective k_T-points PTx pulses is utilized in order to reduce the $B1^+$ field inhomogeneity with reasonable pulse prolongation and

minimal SAR increase. The pulses achieve improved excitation in specific regions like Cerebellum, which CP mode pulses could not excite sufficiently. With an additionally acquired $B1^+$ map, the remaining transmit field variation was successfully counterbalanced, which was not possible using CP mode pulses. Thus more homogeneous quantitative parameter maps of high-quality can be obtained.

Although PTx pulses provide the expected benefits, the acquisition currently suffers from SAR limitations. The MT saturation flip angle had to be reduced at the price of lower CNR. Currently, if MTsat is not required, PTx scans can provide quantitative T_1, T_2^* and PD^* maps at 1mm isotropic resolution of high quality within 2 minutes scan time.

In a future study, we will investigate the use of parallel transmit MT pulses, or different CP mode MT saturation, like TIAMO (13).

Conclusion

We have presented a fast MPM protocol at 7T using skipped-CAIPI 3D-EPI with simple PTx pulses. This sufficiently improved the CNR of T_1w and PDw scans in the Cerebellum, while the MTw scans still suffer from CP mode saturation in the current implementation. With an additional $B1^+$ map acquired, more homogeneous T_1, PD^* and T_2^* maps of high-resolution and high-quality can be obtained throughout the brain.

Acknowledgments

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	CP	PTx	CP	PTx
	T_1w / PDw / MTw		B_1 mapping: TR_2/TR_1	
Resolution [mm^3]	1.0		5.0	
skipped-CAIPI	$2x2_{z1}$		$2x2_{z1}$	
EPI factor	4		5	
Segmentation factor	20		4	
k_T-points	-	3	-	3
(Sub-) Pulse duration[ms]	1.0		1.0	
TE [ms]	4.64, 9.64, 14.64, 29.64		4.6	
TR [ms]	27 / 27 / 45	27 / 27 / 45 (TR_{MT2} −74)	100/20	
Nominal FA [°]	20 / 3 / 4		50	
TA [min:sec]	0:50 / 0:50 / 1:19	0:50 / 0:50 / 1:19 (TA_{MT2} =2:06)	0:10	

Tab. 1 *Sequence parameters of T_1w, PDw, MTw scans and B1 mapping using CP mode and PTx pulses.*

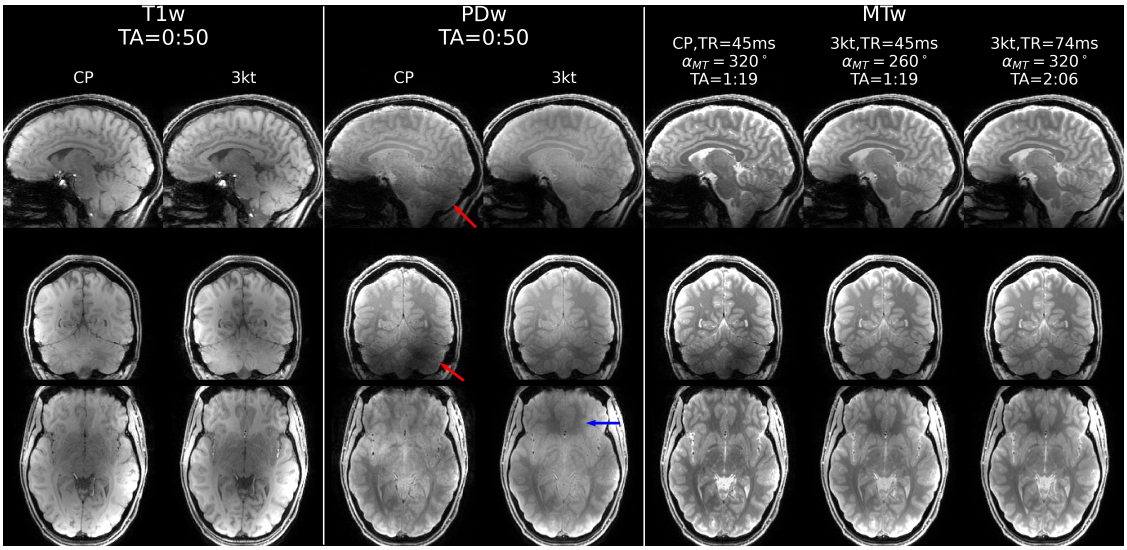

Fig. 1 *Sagittal, coronal and axial view of T_1w, PDw and MTw images acquired using CP mode and PTx pulses. The last column shows the MTw scan with prolonged TR and the same nominal MT flip angle as the CP mode. The acquisition times are listed for each scan. All three MTw scans share the same CP mode MT pulse with different nominal saturation flip angles and TRs in order to match the SAR limits, listed respectively. The ones with a higher FA show slightly better soft tissue contrast.*

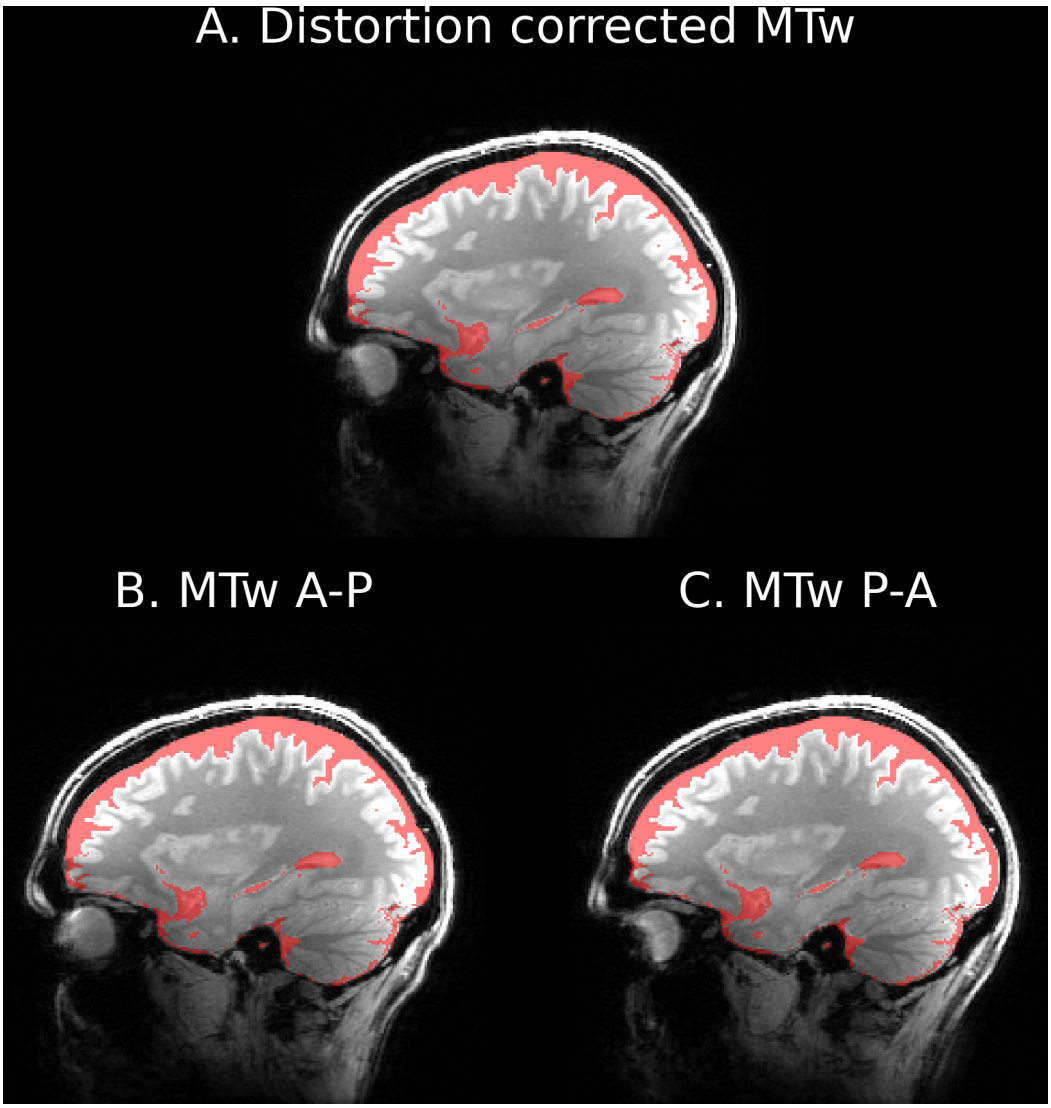

Fig. 2 *Sagittal slices of (A) distortion corrected MTw image using TOPUP (9),(10) as well as MTw image with (B) uncorrected AP and (C) uncorrected PA phase-encoding direction. The CSF mask is generated from the corrected MTw scan and overlaid in red. With a high segmentation factor of 20 (EPI factor of 4), the geometric distortions along the AP direction are neglectable, while imaging speed is much higher than the conventional FLASH for MPM ("EPI factor" 1).*

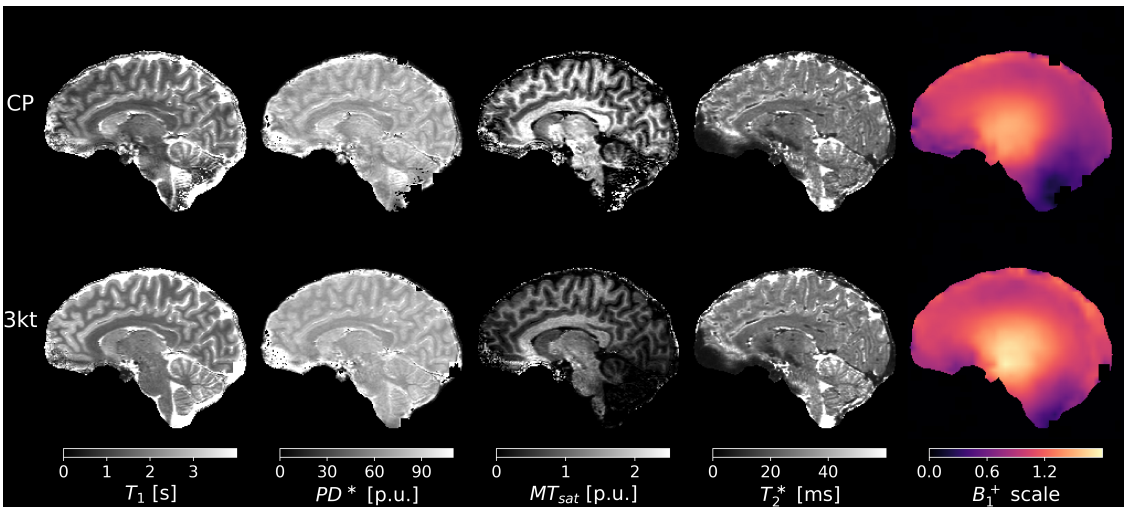

Fig. 3 *A sagittal view of T_1, PD^* MT_{sat} and T_2^* maps using the data acquired with the CP mode and PTx pulses along with the corresponding B1⁺ scale map. The TR is 45ms for both MTw scans. The nominal MT flip angle is 260° for PTx image and 320° for CP. Both MTsat maps have low CNR due to the insufficient MT saturation, especially in the Cerebellum. The PTx B1⁺ scale map shows improved excitation in the Cerebellum compared to the CP map. The PTx T_1 map has higher values than the CP T_1 map and robust voxel estimates throughout the brain.*

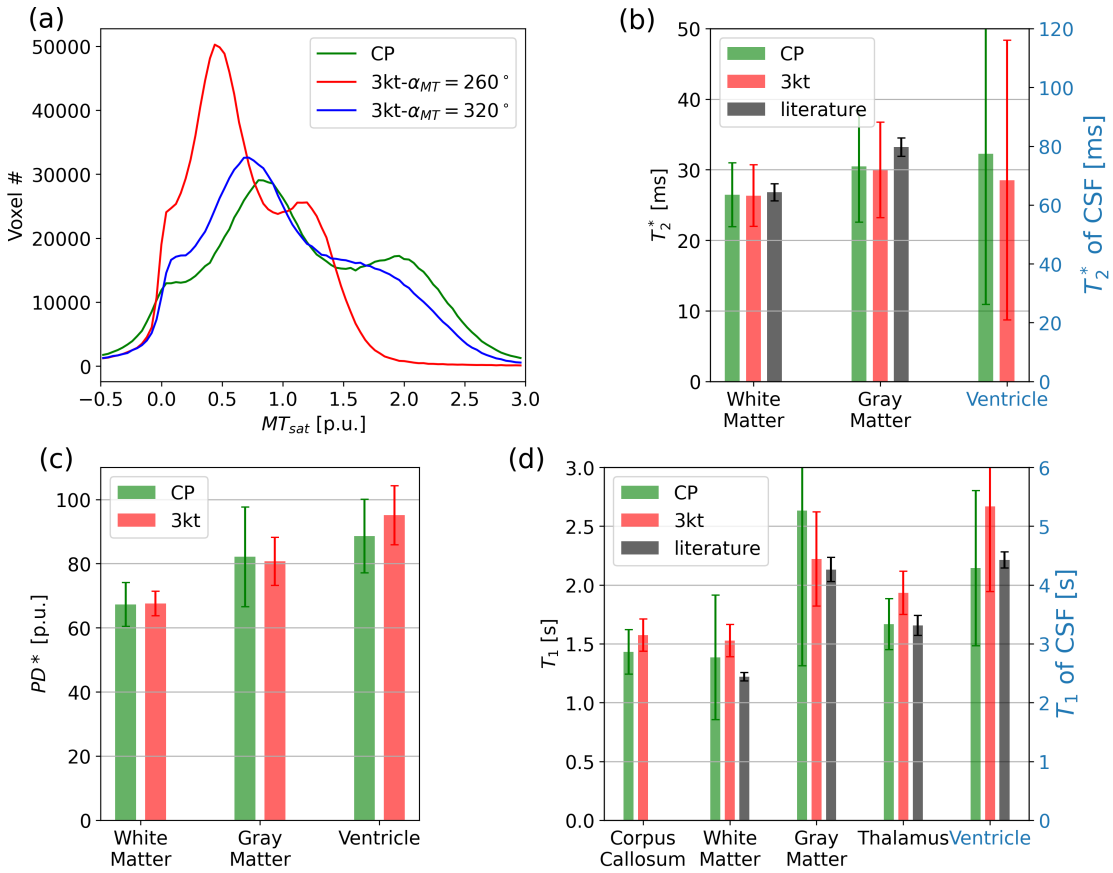

Fig. 4 *(a) Whole-brain MTsat histogram with Cerebellum excluded and (b) T_2^*, (c) PD*, (d) T_1 estimates in different ROIs. The T_2^* literature values are taken from (11) and the T_1 literature values are taken from (12). The bars of CSF in (b) and (d) refer to the second vertical axis. The low MT saturation flip angle (260°) is not sufficient to provide enough saturation effect to clearly separate different modes for CSF, WM and GM.*