Parallel-Transmission-Enabled T1-Weighted Human Brain Imaging for Robust Volumetric and Morphologic Studies at 7T

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Introduction: Considering the demand for regional analysis of the cortical sheet [11], high-quality highly-resolved T1-weighted images of the brain are desired. One of the promises of Ultra High Field (UHF) MRI scanners is to bring finer spatial resolutions due to an increased signal to noise ratio. However, the spatial non-uniformity of the Radio Frequency (RF) transmit profile challenges the applicability of most MRI sequences, where the signal and contrast levels strongly depend on the flip angle (FA) homogeneity. In particular, the MP-RAGE sequence, one of the most commonly employed 3D sequences to obtain T1-weighted anatomical images of the brain, is highly sensitive to these spatial variations. These cause deterioration in image quality and complicate subsequent image post-processing such as automated tissue segmentation at UHF. Therefore, advanced applications such as automated thickness measurements on the cortical sheet are typically only attempted on data acquired at 1.5 or 3 Tesla [1]. In this work, we evaluate the potential of parallel-transmission (pTx) [2] to obtain high-quality MP-RAGE images of the human brain at 7 Tesla.

Methods: To evaluate the performance of the proposed method, four volunteers were scanned with both an investigational 7 Tesla setup and a clinical 3 Tesla system. Our institutional review board approved this study and informed consent was obtained from each participant.

– ***Setup 7T*:** Experimental verification was performed on a Siemens 7T Magnetom scanner (Erlangen, Germany), equipped with an 8-channel pTx-extension. A home-made transceiver-array head coil was used, which consists of 8 stripline dipoles distributed every 42.5° on a cylindrical surface of 27.6-cm diameter, leaving an open space in front of the subject's eyes. Both the 10-sec- and 6-min-averaged RF powers were monitored in real time for each transmit-channel to ensure patient safety and compliance with the SAR guidelines [3]. Sequence parameters were: TI = 1.1 s, TR = 2.6 s, TE = 3.5 ms, IET = FLASH TR = 7.1 ms, FA=6.5°, 256x256x192 matrix in sagittal acquisition, SENSE [4] factor = 1.3, total acquisition time ~8 min.

- ***Setup 3T*:** In addition, each of these volunteers was also scanned at 3T (without parallel transmission). The clinical system used for that purpose was a Magnetom Tim Trio (Siemens, Erlangen) equipped with a whole-body transmit RF coil and a 12-channel receive head coil. In this case, MP-RAGE images were acquired with routinely-used parameters: 1.04x1.0x1.1mm resolution, TI = 0.9 s, TR = 2.3 s, TE/IET = 3.0/7.1ms, FA = 9°, partial Fourier 7/8, 256x230x160 matrix in sagittal acquisition, total acquisition time ~8 min.

- ***Pulse design*:** Calibration measurements for the pTx extension, including B0 and B1-mapping, were performed as described in [5]. Both excitation and inversion pulses were based on the recently introduced k_T-points trajectory [5]. Excitation pulses, involving 5 k_T-points targeting a 6.5° FA throughout the brain, were designed using the spatial domain method [6] in combination with the magnitude least squares approach [7]. The inversion pulses were tailored with an iterative method based on the optimal control approach proposed by Xu et al. [8]. For the specific purpose of designing inversion pulses, our implementation was modified to solve the equivalent magnitude-only optimization problem [9]. The complete procedure was implemented in C++ including GPU-enabled CUDA extensions allowing subject-specific inversion pulse design within a couple of minutes. For comparison, the conventional combination of adiabatic inversions and square excitations were also evaluated at 7T. To this end, the pTx system was configured to mimic a typical quadrature (CP)-mode and a subject-specific optimized coil configuration (RF-shim).

- ***Analysis*:** The impact of the attained image quality on volumetric and morphological studies is quantified by analysis of the outcome from automated tissue classification and evaluation of the cortical ribbon. To this end, both SMP8 (http://www.fil.ion.ucl.ac.uk/spm/) and freesurfer 5.0 (http://surfer.nmr.mgh.harvard.edu/) software packages were used.

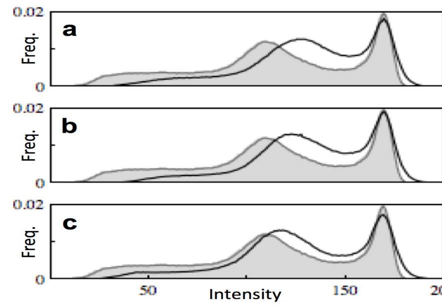

Fig 1: Histogram of the bias-field-corrected voxel signal intensities measured throughout the volume of the brain. Results from the 3 methods used at 7 T are superimposed (black line) on the histogram corresponding to the conventional method at 3 Tesla (gray surface). **a:** CP-mode, **b:** RF-shim, **c:** k_T-points.

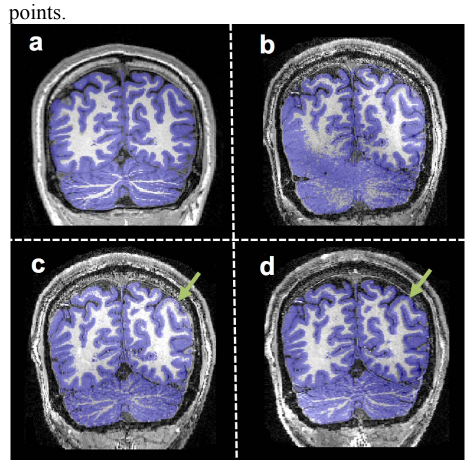

Fig 2: Automated gray/white mater segmentation performed with SPM 8. **a**: 3T, **b**: 7T CP-mode, **c**: 7T RF-shim, **d:** 7T k_T-points.

Results & Discussion: Histograms of the MP-RAGE images resulting from the 3 transmit strategies are shown superimposed on the 3T baseline (Fig. 1). From these, it can be seen how the contrast is regained with the subjects-specific methods, approaching the T1-contrast and image quality normally only achieved at lower fields, thus facilitating automated white matter (WM) and gray matter (GM) segmentation with greater confidence (Fig. 2). This is mostly significant along the peripheral areas of occipital and temporal lobes, where both the RF-shim and k_T-points method show clear improvements compared to the conventional approach. Residual contrast artifacts observed with the RF-shim could be subdued with the k_T-points method (Fig. 2, green arrows). If uncorrected, such artificial contrast variations introduce a bias in volumetric studies. For example, when comparing the cortical GM and subcortical WM volume the conventional approach can underestimate the relative gray matter volume by up to 11%.

Subject	#1	#2	#3	#4
3T	1.07	1.07	1.00	0.99
7T CP-mode	0.95	1.03	0.97	0.92
7T RF-Shim	1.05	1.08	1.01	1.01
7T k_T-points	1.07	1.07	1.00	1.01

Table 1: Measured ratio between cortical gray matter and subcortical white mater (freesurfer).

Due to the elongation of the T1 relaxation time with increased field strength, the absolute contrast remains slightly lower than what was achieved at 3T. Nonetheless, in terms of robustness, the k_T-points method at 7T could ultimately outperform the conventional method applied at lower field strengths due to the well-controlled excitation fidelity. Without pTx, the excitations at 3T are limited to 12% excitation fidelity, where as the k_T-points method at 7 Tesla demonstrated excitation errors as low as 7% [5]. When mapping the cortical thickness with our 3T configuration, accurate GM/WM delineation can be challenging in the prefrontal cortex, resulting in relatively low values, compared to those reported based on 1.5T measurements [10]. The here-proposed k_T-point method applied at 7T produces more consistent cortical thickness values, clearly revealing the thicker gyral and thinner sulcal regions in the pre-frontal cortex (Fig. 4).

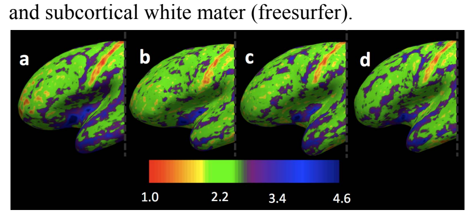

Fig 4: MRI based cortical thickness measurements averaged over 4 subjects. **a**: 3T, **b**: 7T CP-mode, **c**: 7T RF-shim, **d:** 7T k_T-points.

Conclusion: Although there has been some suspicion in the neuro-radiology community that high field systems are not competitive for T1-weighted imaging, this study indicates that a pTx-enabled 7T system is able to produce high-quality better resolved T1-weighted images with allotted time equivalent to those used at lower field strength.

References: [1] Du, et al., Brain; 130:1159-1166 (2007). [2] Han, et al., NeuroImage; 32:180–194 (2006). [3] Katscher, et al., MRM; 49:144-150 (2003). [4] Boulant, et al., ISMRM; p.3850 (2011). [5] Pruessmann, et al., MRM; 42:952–962 (1999). [6] Cloos, et al., DOI.10.1002/mrm.22978. [7] Grissom, et al., MRM; 56:620-629 (2006). [8] Setsompop, et al, MRM; 59: 908-915 (2008). [9] Xu, et al., MRM; 58:547-560 (2008). [10] Cloos, et al., 8th Minnesota UHF workshop p.71 (2011). [11] Fishl, et. al., PNAS; 97 :11050–11055 (2000).