Magnetization transfer (MT) of human brain at 7T in the context of a 3D multi-parameter mapping protocol

Hampus Olsson[1], Mads Andersen[2,3], Jimmy Lätt[4,5], Ronnie Wirestam[1], and Gunther Helms[1,3]

[1]Clinical Sciences Lund, Medical Radiation Physics, Lund University, Lund, Sweden, [2]Philips Danmark A/S, Philips Healthcare, Copenhagen, Denmark, [3]National 7T Facility, Lund University, Lund, Sweden, [4]Centre for Medical Imaging and Physiology, Skåne University Hospital, Lund, Sweden, [5]Clinical Sciences Lund, Department of Radiology, Lund University, Lund, Sweden

Synopsis

3D multi-gradient echo MRI can be used to estimate T_1, T_2*, PD and the magnetization transfer (MT), which is increasingly used for multi-parametric mapping (MPM) of human brain. The increased polarization at 7T compared to lower B_0 allows for increased spatial resolution or reduced scan times. However, SAR restrictions imposed on the MT pulse and B_1 inhomogeneity pose challenges. In this work, we propose a protocol for MPM of human brain at 7T with special attention paid to eliminating bias when mapping MT_{sat} while obtaining submillimeter isotropic spatial resolution in under 12 minutes with acceptable SNR.

Introduction

3D multi-gradient echo MRI is a versatile and quick method to estimate maps of tissue parameters such as T_1, T_2*, proton density (PD) and magnetic susceptibility. At clinical field strengths, B_0, the method is also used to quantify magnetization transfer (MT)[1] or to calculate the MT saturation, MT_{sat}, using a dual flip angle (DFA) experiment[2]. MT contrast is evoked by applying a high-energy off-resonance saturation pulse prior to excitation. The average RF power may be curtailed by SAR limits, especially at 7T.

At 3T, gradient-echo (GRE) multi-parametric mapping (MPM) for quantitative structural MRI of the human brain takes about 20 mins[3], but requires accurate flip angle mapping to account for B_1^+ inhomogeneity. The higher polarization at 7T will allow for increased spatial resolution or reduction of the scan time by parallel imaging. In addition, the T_2* contrast increases with B_0.

Based on an established 3T protocol, we optimized MPM of human brain at 7T with special attention paid to elimination of bias in MT_{sat}.

Methods

Healthy adult subjects were scanned on a 7T Philips Achieva MR system (Philips Healthcare, Best, NL), using a dual-channel transmit head coil with 32 receive elements (Nova Medical, Wilmington, MA) after giving informed written consent. Eight sagittal non-selective volumes were acquired from bipolar gradient echoes at 670 Hz/px bandwidth. The minimum T_E=1.97 ms and maximum T_E=15.76 ms (equidistant, fat water in-phase) yielded T_R=18 ms without the MT pulse, and 2x SENSE[4] was applied in both phase encoding directions. The optimization procedure followed the following main steps:

1. The “block” excitation RF pulse was replaced by an asymmetric sinc pulse to reduce the sensitivity to the increased B_0-inhomogeneity at 7T. To determine the flip angles used in DFA, the flip angle, α, was varied from 2° to 27° (Figure 1).

2. A main-lobe sinc pulse of 4 ms duration was used for MT saturation. The SAR limit was reached at a saturation α of about 180° at T_R=28 ms. The frequency offset was varied from 0.75 kHz to 2.00 kHz (Figure 2).

3. The excitation α of the MT-weighted (MT-w) sequence was varied from 2° to 8° (Figure 3).

4. The maximum B_1^+ amplitude of the excitation pulse was varied, using 5, 9, and 14 μT (Figure 4).

Flip angle mapping was performed using DREAM[5] and B_1^+ bias in the PD, T_1, and MT maps were corrected for post-hoc[3]. Pixel intensities were scaled to physical signal (in [a.u.]). Post-processing and evaluation were performed in MATLAB R2016a using the hMRI toolbox[6].

Results

1. A linear plot of the VFA signal revealed the Ernst angle and incomplete spoiling at α>20° (Figure 1). Thus, α for DFA was chosen as 4° (PD-w) based on the median Ernst angle and 18° (T_1-w) to avoid spoiling bias[7,8].

2. Direct saturation was seen with MT pulses of lower frequency offsets below 2.00 kHz and the offset were thus set to 2.00 kHz (Figure 2).

3. Consistent MT maps were observed at flip angles below 8°, except for broadening of the CSF peak (Figure 3). The excitation flip angle was set to 4° to keep the free water saturation smaller than MT_{sat} analogous to ref., [2], while still attaining acceptable SNR.

4. Peak B_1^+ amplitude affected T_1 and MT_{sat}, with increasing inhomogeneity of T_1 and overestimation of MT_{sat} (Figure 4). Hence, a maximum B_1^+ of 5 μT was chosen.

With this optimized 7T protocol, multi-parameter maps of 0.9 mm isotropic resolution are obtained in 10-12 mins depending on FoV (Figure 5). MT_{sat} exhibits a high GM-WM contrast, especially in deep brain, but requires correction of residual B_1^+ inhomogeneities[2].

Discussion

Aiming at reducing bias in the semi-quantitative MT_{sat} maps, we optimized a GRE-based MPM protocol at 7T. Limitations of average power by SAR were met by reducing the energy of the MT pulse and a moderately longer TR[3]. This led to lower semi-quantitative MT_{sat} values, despite being corrected for T_1. Contrary to 3T[2], the calculated MT_{sat} at 7T deviated distinctly at high and low B_1^+ (data not shown) and this was corrected post hoc using a B_1^+ map[3]. T_1 values agreed with

literature[9] but suffered from unwanted MT effects at high peak B_1^+ amplitudes[10]. The scan time was about 50 % compared to 3T. The gain in SNR per time is under investigation. In addition, the multi-echo phase images can be used for quantitative susceptibility mapping (QSM).

Conclusion

MT mapping within an MPM protocol at 7T is feasible but requires B_1^+ correction and control of inherent MT effects by the excitation pulses.

Acknowledgements

Dr. Burkhardt Maedler, Philips Healthcare, for advice on MT pulse implementation.

References

1. Sled, J.G. and G.B. Pike, Quantitative imaging of magnetization transfer exchange and relaxation properties in vivo using MRI. Magn Reson Med, 2001. 46(5): p. 923-31.

2. Helms, G., et al., High-resolution maps of magnetization transfer with inherent correction for RF inhomogeneity and T1 relaxation obtained from 3D FLASH MRI. Magn Reson Med, 2008. 60(6): p. 1396-407.

3. Weiskopf, N., et al., Quantitative multi-parameter mapping of R1, PD(*), MT, and R2(*) at 3T: a multi-center validation. Front Neurosci, 2013. 7: p. 95.

4. Pruessmann, K.P., et al., SENSE: sensitivity encoding for fast MRI. Magn Reson Med, 1999. 42(5): p. 952-62.

5. Nehrke, K. and P. Bornert, DREAM--a novel approach for robust, ultrafast, multislice B(1) mapping. Magn Reson Med, 2012. 68(5): p. 1517-26.

6. Balteau, E., et al., hMRI – A toolbox for using quantitative MRI in neuroscience and clinical research. Neuroimage (under revision).

7. Dathe, H. and G. Helms, Exact algebraization of the signal equation of spoiled gradient echo MRI. Phys Med Biol, 2010. 55(15): p. 4231-45.

8. Helms, G., et al., Identification of signal bias in the variable flip angle method by linear display of the algebraic Ernst equation. Magn Reson Med, 2011. 66(3): p. 669-77.

9. Rooney, W.D., et al., Magnetic field and tissue dependencies of human brain longitudinal 1H2O relaxation in vivo. Magn Reson Med, 2007. 57(2): p. 308-18.

10. Al-Abasse, Y. and G. Helms. Influence of pulse length and shape on variable flip angle T1 mapping of human brain. in Proc ISMRM. 2016. 24: p. 614.

Figures

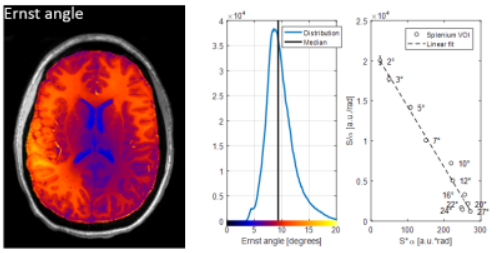

Figure 1. Pseudo-color map (left) and whole-brain histogram (middle) of the actual Ernst angle, i.e., with B_1^+-inhomogeneity. The median Ernst angle of 9.3° (black line) would require optimal settings of α_{PD}=4° and α_{T1}=22°. However, a linear plot of the variable flip angle (VFA) signal, S, (right) at high B_1^+ in splenium revealed incomplete spoiling at nominal flip angles α_{nom}≥20°. Hence, α_{T1}=18° was chosen, thus reducing bias at the cost of reduced SNR[7,8].

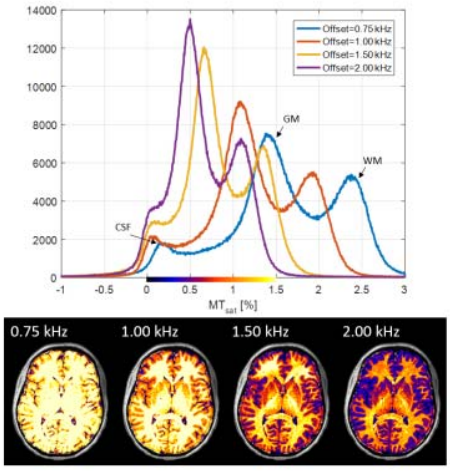

Figure 2. Pseudo-color maps of MT_{sat} at different frequency offsets of the MT pulse with accompanying whole-brain histograms. Whole-brain histograms: Direct saturation of the free water pool at offsets below 2.00 kHz (blue, red, yellow) is indicated by the shift of the CSF peak from zero and by an additional shift of the GM and WM peaks relative to CSF as described in ref., [2]. Reducing the direct saturation bias comes at a cost of reduced dynamic range in the MT_{sat} values. Based on these results, a frequency offset of 2.00 kHz was determined for the protocol.

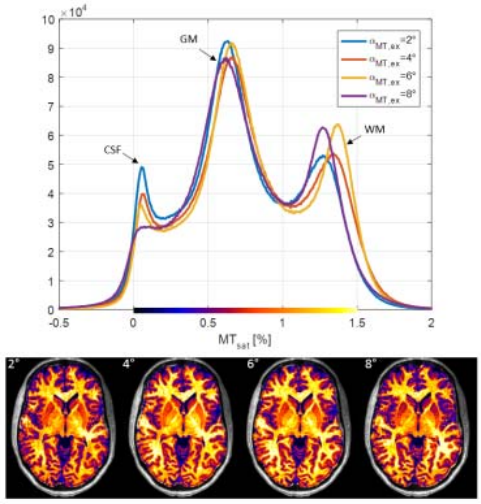

Figure 3. Pseudo-color maps of MT_{sat} with increasing excitation flip angle, $\alpha_{MT,ex}$, of the MT-w sequence with accompanying whole-brain histograms. The maps are reasonably consistent for $\alpha_{MT,ex} \leq 6°$. However, the broadening of the CSF peak in the histograms with increasing $\alpha_{MT,ex}$ reflects a decrease in SNR. The low SNR of the $\alpha_{MT,ex}=2°$ map appears as a broadening of the WM mode. To keep saturation of the free water pool smaller than MT_{sat} but maintaining good SNR $\alpha_{MT,ex}=4°$ was chosen for the protocol.

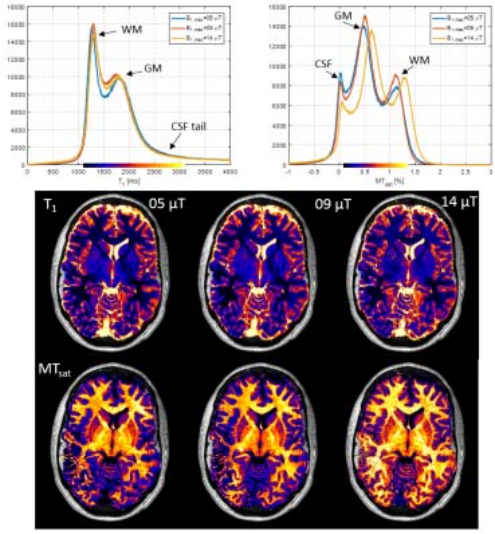

Figure 4. Pseudo-color maps of T_1 and MT_{sat} with increasing peak B_1^+ of the excitation pulse with accompanying whole-brain histograms. The T_1 map was more homogeneous at low peak B_1^+, as seen in the frontal and posterior WM. At high peak B_1^+, MT_{sat} was offset to higher values. This is reflected in the histograms, although affected by the spatially inhomogeneous B_1^+. To minimize effects from B_1^+ bias and unwanted MT effects[10] a peak B_1^+ amplitude of 5 µT was chosen.

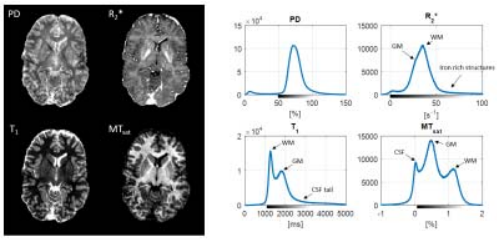

Figure 5. Results from the finished MPM protocol described. PD, R_2*, T_1 and MT_{sat} maps with accompanying whole-brain histograms. Note the contrast in the basal ganglia of the MT_{sat} map. Peak values for CSF, GM and WM denoted by arrows in the histograms. Peak MT_{sat} values: CSF=0.01 %, GM=0.47 %, WM=1.12 %. Peak T_1 values: WM=1263 ms, GM=1828 ms which agrees well with literature[9]. Peak R_2* values: GM=27.7 s^{-1}, WM=34.7 s^{-1} and iron rich structures above

50 s^{-1}.