K_T-POINTS-BASED INVERSION PULSE DESIGN FOR TRANSMIT-SENSE ENABLED MP-RAGE BRAIN IMAGING AT 7T

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Introduction: Among the advantages of the Transmit-SENSE (pTx) method [1] is the ability to facilitate short low SAR excitation pulses with excellent flip-angle (FA) homogeneity at high field [2,3]. In this framework, large tip angle (LTA) pulses are of particular interest as they could provide a viable alternative to the SAR-demanding adiabatic solutions. Considering for example the widely-used MP-RAGE sequence [4], the conventional approach typically adopts the adiabatic hyperbolic secant solution to facilitate homogeneous inversion at 1.5T and higher [5]. In this abstract, we demonstrate the k_T-points method [3] in the MP-RAGE sequence for high-resolution T1-weighted brain imaging at 7 Tesla, omitting adiabatic pulses by introducing the k_T-points-based inversion pulse design.

Methods: 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 [6]. Our institutional review board approved this study and informed consent was obtained from each of the participants.

Calibration measurements, including B0- and B1-mapping (5-mm isotropic resolution), were performed as described in [3]. Small tip-angle excitation (STA) pulses, involving 5 k_T-points targeting a 6.5°-FA throughout the brain, were designed using the spatial domain method [7] in combination with the MLS approach [8], initially targeting a phase distribution corresponding to the circularly polarized (CP) mode.

The inversion pulse was tailored with an iterative method. First an initial 180° candidate was designed based on the STA approximation applied to 14 k_T-points symmetrically distributed around the k-space center along k_x, k_y, and k_z (step 1). Subsequently the optimal control approach [9] was applied to account for the non-linear behavior of the Bloch-equations for LTA (step 2). Our implementation differs slightly from the one demonstrated in [9], allowing a magnitude-only optimization problem to be solved. To this end, we minimize the normalized root mean square inversion error (NRMSIE $= \sqrt{\sum_{\boldsymbol{r}}(M_z(\boldsymbol{r})+1)^2}\,/\sqrt{N}$ where $\boldsymbol{r}$ is a voxel location in the brain and N is their number). In addition, the ΔB_0 evolution was encompassed in the optimization procedure, including the option to solve for multiple frequencies simultaneously [10], thus allowing a margin to be incorporated to acount for inaccuracies in the measured ΔB_0–field. The peak amplitude of the designed waveforms was constrained to the maximum voltage available on each channel, and their cumulative energy was constrained to 1.8 J per transmit channel (step 3). Inspired by [11], the Nelder–Mead method was applied to search k-space for improved k_T-point locations (step 4). Steps 2-4 were iterated until the NRMSIE dropped below 5%, or the maximum number of iterations was reached. Although, in our current STA implementation the sub-pulse shapes are square, our LTA design method allows the wave forms to evolve freely on a 1μs raster time. The complete procedure was implemented in CUDA allowing subject-specific pulse design within a couple of minutes.

In order to establish the performance of the proposed pulse design, three different transmit strategies were applied to the MP-RAGE sequence at 7 Tesla: synthesized CP-mode with conventional combination of sech inversion and square excitations, RF-shim with same RF pulses, and the above-described method. Sequence parameters were: TI=1.1s, TR=2.6s, TE=3.5ms, FLASH TR=7.1ms, FA=6.5°, 256x256x192 matrix, 0.8-mm isotropic. Various design aspects were evaluated, including the initial k-space trajectory and off-resonance behaviour. Furthermore, several volunteers were also imaged at 3T for comparison (Siemens Magnetom Tim Trio without pTx).

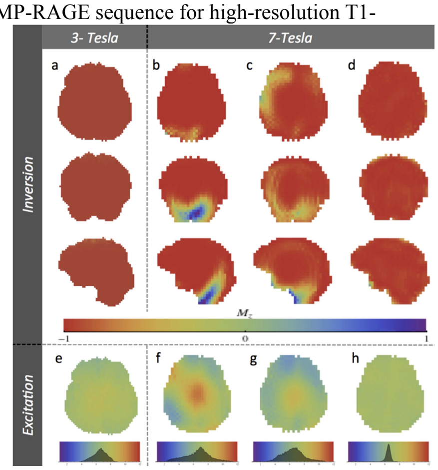

Fig 1: A comparison of the different inversion and excitation pulses applied to a representative subject (simulation only). The inversion pulses: **a)** hyperbolic secant inversion pulse at 3T, **b)** CP-mode with a 7-ms hyperbolic secant inversion pulse, **c)** RF-shim with the same pulse, and **d**: k_T-point-based 6.1-ms inversion pulse. The FA-maps corresponding to the excitations are shown at the bottom row.

Results & Discussion: Within our SAR limitations, the sech pulse in CP mode does not seem to reach the adiabatic condition necessary to homogenize the inversion at all points within the brain (Fig. 1**b**). Adopting a suitable RF-shim greatly enhances the performance of the sech inversion at 7 Tesla (Fig. 1**c**). However, small residual defects may remain due to limitations on the peak power provided by the amplifiers (Table 1). By adopting the proposed k_T-points-based approach, excellent inversion fidelity was obtained (Fig. 1**d**), comparable to what is commonly achievable with adiabatic pulses at 3T (Fig. 1**a**). Histograms of the MP-RAGE images resulting from the 3 transmit strategies are shown superimposed on the 3T baseline (Fig. 2). These images demonstrate the regain in contrast due to the improved excitation and inversion fidelity, also visible in Fig. 3 (arrows).

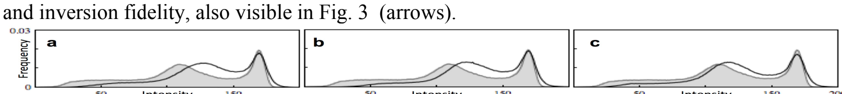

Fig 2: Histogram of the bias-field-corrected voxel signal intensities measured throughout the volume of the brain measured (same volunteer). Results from the 3 methods used at 7T are superimposed (black line) on the results corresponding to the conventional method at 3T (gray surface). **a:** CP-mode, **b:** RF-shim, **c:** k_T-points.

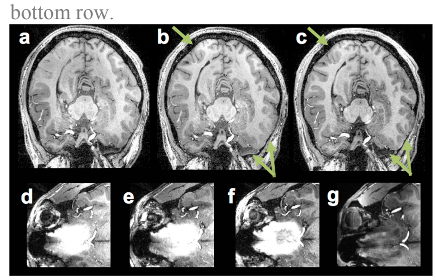

Fig 3: Top: axial slices from the MP-RAGE images obtained with the 3 different methods at 7T. **a:** CP-mode, **b:** RF-shim, **c:** k_T-points. Bottom: Axial section just above the sphenoid sinus: **d:** CP-mode, **e:** RF-shim, **f:** k_T-points, **g:** k_T-points with locally extended bandwidth.

Regarding magnetic susceptibility effects, whereas the excitation pulses have a sufficiently large bandwidth to cover affected areas such as above the mouth [3], both sech and k_T-points-based inversion pulses demonstrate a more limited frequency response (Fig. 3**d-f**). Although the tailored waveforms take the measured spatial distribution of the B0-field into account, undesired effects may still appear at borders with the inter-cranial cavities (Fig. 3**f**). These effects may be attributed to deviations from the measured B0-field especially due to the limited spatial resolution of the mapping procedure. Rather than incorporating cumbersome high resolution B0-field maps, a larger bandwith can be enforced by optimizing the RF-waveforms over a range of frequencies [11], and just locally. Although this approach is still under evaluation, initial measurements suggest that it is generally sufficient to enforce a 25% margin around the measured B0-field near the intracranial cavities (Fig. 3**g**). In terms of SAR, the proposed method provides a significant reduction in total energy deposition compared to the conventional sech inversion pulses (Table 1). However, when comparing different k-space configurations, we observe that increased pulse duration or number of k_T-points do not necessarily reduce the cumulative energy deposition as more energy has to be spent to fight the B0-offset effects.

	Method	Duration	Energy	NRMSIE
		ms	J	%
3-Tesla	CP	8.2	12.0	3
3-Tesla	CP	10.2	14.9	1
7-Tesla	CP	7.0	11.5	22±8
7-Tesla	CP	8.5	14.0	18±6
7-Tesla	CP	10.0	16.4	17±5
7-Tesla	RF shim	7.0	8.1±0.4	14±4
7-Tesla	RF shim	8.5	9.8±0.4	10±3
7-Tesla	RF shim	10.0	11.6±0.5	11±4
7-Tesla	k_T-8	4.4±0.3	9.5±1.5	6±3
7-Tesla	k_T-14	5.9±0.7	7.3±0.6	5±1
7-Tesla	k_T-20	6.8±0.5	7.8±2.4	5±1

Table 1: Simulated gain observed on the inversion pulse performance when lengthening its duration, based on B_1^+-maps measured at 7 Tesla in 8 volunteers, where "k_T-#" indicates the proposed method visiting # k-space locations.

Conclusion: MP-RAGE acquisition with both excellent excitation and inversion fidelity throughout the volume of the human brain at 7 Tesla, has been demonstrated by means of the LTA-enabled k_T-points method in the framework of pTx. Starting from a symmetric distribution of k_T-point locations approximating the linear class of LTA pulses [12] robust pulse design with favorable SAR performance compared to the adiabatic solution was shown. Nonetheless, alternative initial k_T-point locations could possibly allow further reductions in RF-power or pulse duration.

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