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-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-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 transceive-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-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-points symmetrically distributed around the k-space center along kx, ky, and kz (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) $\sqrt{\sum (M_r(r) + 1)^2/N}$ where r is a voxel location in the brain and N is their number). In addition, the $\Delta B_0$ evolution was encompassed in the optimization procedure, including the option to solve for multiple frequencies simultaneously [10], thus allowing a method to be incorporated to fields inhomogeneous in the measured $\Delta B_0$-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-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 quadrature, 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-pulse with conventional combination of each inversion and square excitations, RF-shim with same RF pulses, and the above-described method. Sequence parameters were: TR=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).

Results & Discussion: Within our SAR limitations, the echo pulse in CP mode does not seem to reach the adiabatic condition necessary to homogenize the inversion at all points within the brain (Fig. 1b). Adopting a suitable RF-shim greatly enhances the performance of the echo inversion at 7 Tesla (Fig. 1c). However, small residual defects may remain due to limitations on the peak power provided by the amplifiers (Table 1). By adopting the proposed k-points-based approach, excellent inversion fidelity was obtained (Fig. 1d), comparable to what is commonly achievable with adiabatic pulses at 3T (Fig. 1a). 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).

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-points method in the framework of pTx. Starting from a symmetric distribution of k-points 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 inversion k-points locations could possibly allow further reductions in RF-power or pulse duration.

References:

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-point-based 6.1-ms inversion pulse. The FA-maps corresponding to the excitations are shown at the bottom row.

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-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-points. Bottom: Axial section just above the sphenoid sinus: d: CP-mode, e: RF-shim, f: k-points, g: k-points with locally extended bandwidth.

<table>
<thead>
<tr>
<th>Method</th>
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<tr>
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<td>14.0</td>
<td>18.6</td>
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<tr>
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<tr>
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<td>7.8±2.4</td>
<td>5.2</td>
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</table>

Table 1: Simulated gain observed on the inversion pulse performance when lengthening its duration, based on B1+-maps measured at 7 Tesla in 8 volunteers, where “k-n” indicates the proposed method visiting # k-space locations.