K_t points: Fast Three-Dimensional Tailored RF Pulses for flip-angle homogenization over an extended volume

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Introduction: Transmit-SENSE [1] gives the opportunity to implement short excitation pulses with good flip-angle (FA) homogeneity at high field. For slice-selective pulses, this was demonstrated using a spoke k-space trajectory [2, 3]. For the first time, a novel pulse design is presented which enables sub-millisecond pulses with excellent FA homogenization over an extended volume corresponding to that of a human brain.

Theory: The method, which we shall name "k_T-points", homogenizes the FA over substantial volumes. It is inspired from the sparse characteristics of the spokes method [2,3]. The novelty lies in the use of blips of magnetic field gradients along three orthogonal directions to navigate in the 3D k-space, and transmit RF in stationary k-space locations, the so-called k_T-points, where energy is particularly needed to fight the RF inhomogeneities. In addition, since the sub-pulses are now non-selective a priori, their durations can be adjusted to either optimize the total pulse duration or lower the SAR. The location of the k_T-points is critical. Taking the difference of the Fourier transforms of the FA distributions obtained with the circularly polarized (CP) mode (Fig. 1, A-C) and the homogeneous target distribution yields dominant frequency components clustered around the DC component (Fig. 1, D-F), when the RF wavelength is only slightly smaller than the sample under study, which is typically the case of a human head between 3 and 12T. It thus indicates that the target FA distribution can in principle be obtained by exciting a small number of frequency components.

Methods: Experimental verification was performed by implementation of the designed RF pulses on a Siemens 7T Magnetom scanner (Erlangen, Germany), equipped with an 8-channel transmit array. The AC84 gradient head coil allowed gradient amplitudes up to of 50mT/m and slew rate of 400T/m/s. A home-made transmit-array head coil was used (Fig. 2, top), which consists of 8 stripline dipoles distributed every 40-degrees on a cylindrical surface of 27.6-cm diameter, leaving an open space in front of the patient's eyes. All dipoles were tuned ideally to the proton Larmor frequency at 7 Tesla, matched identically to a 50-Ohm line impedance. Measurements were performed in a 16-cm spherical gel-phantom mimicking the dielectric and conductive properties of an average human head [5]. B1-maps (Fig. 2, Bottom) were obtained using the actual flip angle (AFI) sequence [6] including RF-spoiling improvements [7] and two additional echoes for ΔB0 mapping [8] (sequence parameters: TR1/TR2= 66/333ms, TE1/TE2/TE3/TE4=3/3/4/5ms, 6-mm isotropic resolution with a 32x32x40 matrix). Excitation pulses were designed to homogenize the FA over 22 partitions (132 mm along z) using a k-space trajectory visiting 9 of the most energetic Fourier components (Fig. 3, left). Excitation pulses were designed in Mathematica (Wolfram Research, Champaign, IL, USA) using the Small Tip Approximation in the spatial domain [4], and the local variable exchange method to solve the Magnitude Least Square problem [3]. Repeating the design procedure over several iterations, sub-pulse durations were optimized to minimize the total pulse duration. Finally, we used the AFI sequence to measure the FA obtained when using the RF solutions. For comparison, the FA associated with the CP mode was also measured by aligning the phases of the individual B1 maps in the centre of the phantom.

Results: Targeting a 15° FA resulted in a 950-µs excitation pulse (Fig. 3), which produced a 7.3% NRMSE (normalized root mean square error over the volume), i.e. 15 ± 1.1° (Fig. 1,G-I). Compared to the CP mode (23% NRMSE - Fig. 4,A-C), the Max/Min FA was reduced from 23.3/4.9° to 18.0/11.4°. Note that in the CP mode, the low FA near the top of the phantom is due to the aperture in the coil. Comparing experimental results with full Bloch simulations returned a correlation factor of 99.7%, indicating excellent agreement between theory and experiment. Optimization of the sub-pulse durations converged to a local minimum after 3 iterations. Based on the performance of an Intel core 2 duo 2.4-Ghz with 4-GB RAM, the pulse design could be performed in roughly 5 min.

Discussion and Conclusion: For the first time it was demonstrated that 3D homogenization of the FA through an entire object like a human brain is possible at high field with sub-millisecond Transmit-SENSE pulses. Iterative optimization of the sub-pulse durations provides a convenient method to reduce SAR by constraining the maximum power. However, in order to obtain good FA homogeneity with short pulse duration, the positioning of the k_t points is crucial. Further reduction in pulse duration could be possible by pulsing RF while moving between k-space locations. Eventually, the pulses generated here could be used as small excitations in 3D sequences such as FLASH or MP-RAGE. Extending this work beyond the small flip angle regime could allow such pulses to be implemented in virtually any 3D sequence, with performance expected to increase with the number of transmit channels available.

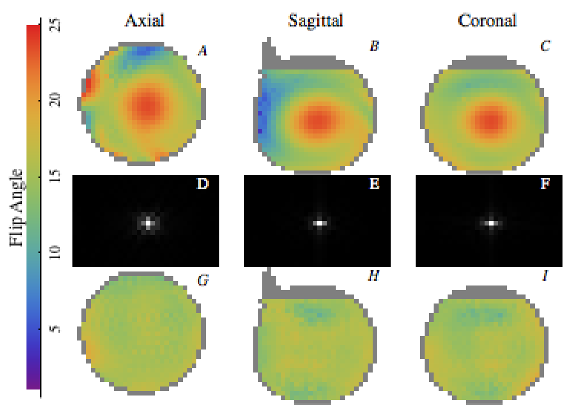

Figure 1: A-C) FA distribution obtained with the CP-mode in central *axial*, *coronal* and *transverse* plane. D-E) Absolute difference between the Fourier transforms of the CP-mode and the ideally uniform excitation in the corresponding k-space planes. G-I) The flip-angle distribution in the same *axial*, *coronal* and *transverse* planes, using the proposed method.

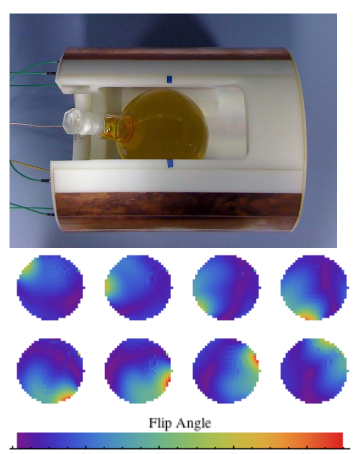

Figure 2: Top) Coil used in the experimental setup. Bottom) Central axial slice of the eight B1-maps used for the RF pulse design.

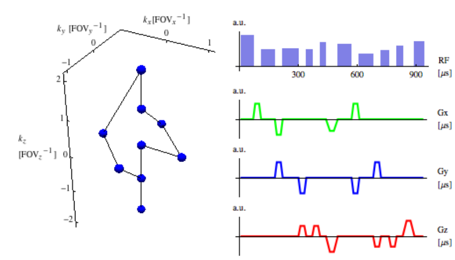

Figure 3: Left) K-space trajectory obtained selecting only 9 of the most energetic Fourier components. Right) Gradients and total RF power summed over all 8 transmit channels. No RF pulsing occurs while the magnetic field gradients are on.

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