Large Tip Angle Segmented RF Design for Multi-Dimensionally Selective Imaging and Spectroscopy with Parallel Transmit

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Introduction

Multi-dimensionally selective RF pulses require a k-space trajectory of the same dimensionality, i.e., ideally, a fast single shot 2D or 3D sampling scheme in transmit (TX) k-space. For target patterns with a high spatial definition, the gradient amplitude and slew rate typically impose long pulse durations rendering the technique prone to various artifacts. However, for inner volume imaging and arbitrary voxel selective spectroscopy, this localization is desirable as it allows for anatomically selective imaging with increased resolution [1], avoiding pulsation artifacts from outside the ROI [2] and reduction of partial volume effects from non-anatomical voxels in MR spectroscopy (MRS). Previously, certain artifacts resulting from long pulse durations have been alleviated by compensation for B0 inhomogeneities in the RF design by taking into account off-resonances [3] or signal decay [4] during the excitation. Alternatively, acceleration of selective pulses using parallel transmit (PEX) [5-7] or splitting of the pulse into segments [8] may mitigate these problems by shortening the pulses. Especially in MRS, short RF pulses are necessary to maintain a sufficient bandwidth for excitation of the metabolites of interest. However, segmented RF excitation in MRS has been limited to small tip angles as signal addition from separate experiments required the linearity of the Bloch equation in this regime.

In this work, a segmented RF design algorithm for large tip angle pulses capable of additional PEX acceleration is described for multi-dimensionally selective excitation and demonstrated in simulation and a phantom for a segmented 2D trajectory. As the optimizations of the individual segments are independent, the nonlinear step of the proposed algorithm can be straightforwardly parallelized.

Methods

Of primary importance is the preconditioning of the large tip angle design problem such that the signal from several repetitions can be added, i.e., the flip angle distributions generated by each segment need to be chosen such that the transverse magnetization distributions add up to the target pattern. Note that in the small tip angle approximation (STA), where the flip angle is proportional to the absolute value of the transverse magnetization, this is always the case. Therefore, one starts with a pulse designed in the STA and divides the total pulse into N segments according to the trajectory design. Fig. 1 shows a 2D example of a segmented radial trajectory (left) with N=50 and N=12, respectively. Subsequently, an STA simulation, starting from longitudinal magnetization, is performed for each individual segment, yielding a complex magnetization distribution M_s (see Fig. 2), where s=1…N counts the segments. All M_s are then scaled up by a common factor such that, e.g., for a nominal design flip angle of 90°, the maximum magnitude across all M_s equals sin(90°). Figure 2 (left) shows an example for such a single segment target. In this way the relative weights of the excitation across segments are maintained. From M_s, target flip angle distributions are calculated via $\alpha_s = \arcsin(|M_s|)$; the target phase φ_s is maintained from the small tip angle solution. Note that phase relaxed RF design is not possible in this method, since the phase is essential in the subsequent addition of signals. Finally, an optimal control design step [10] is carried out to optimize the STA pulse to meet the target (α_s, φ_s). Experiments based on this design can be accelerated by reducing the gradient encoding and introducing B_1 encoding in the pulse design via parallel transmission. All the pulses for the presented example could in principle also be calculated using Shinnar-LeRoux filter design as the segments constitute projections. However, the presented method is neither restricted to radial nor to 2D. Experiments were carried out on a 3 T human MR scanner (Siemens MAGNETOM Trio, A Tim System) with 8-channel TxArray extension and an 8-channel parallel transmit body coil.

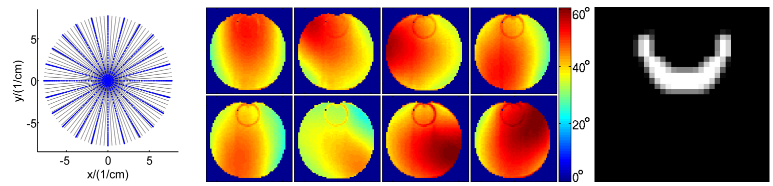

Fig. 1: Left: Radial trajectory in TX k-space with 50 segments (fully sampled, gray lines) and with 12 segments (accelerated, blue dots), segmentation is performed by cutting in the TX k-space center; Middle: 8-channel flip angle maps [9] in a doped water bottle phantom for a rectangular reference pulse; Right: target pattern on a 32x32 design grid.

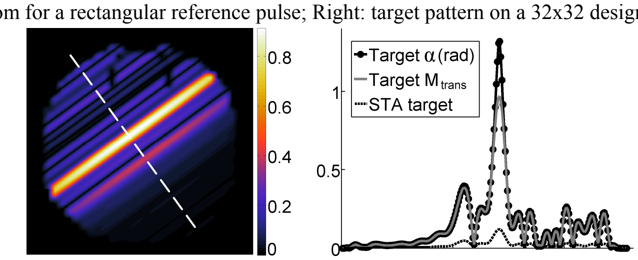

Fig. 2: Left: Transverse magnetization target pattern for a single segment pulse; Right: Original transverse magnetization target along the section indicated on the left for a STA pulse (dashed line), desired scaled transverse magnetization (gray solid line) and corresponding flip angle design target (dotted line)

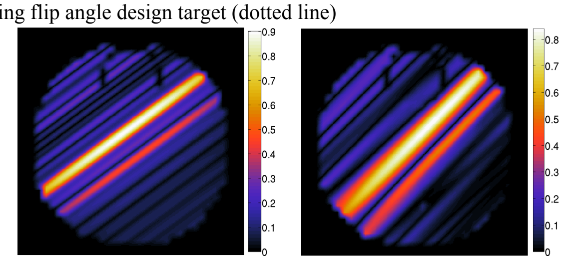

Fig. 3: Simulated single segment excitations for the non-accelerated case, essentially representing a projection of the target pattern (left), and of the accelerated case, where significant B1 encoding visibly alters the pattern from a projection (right).

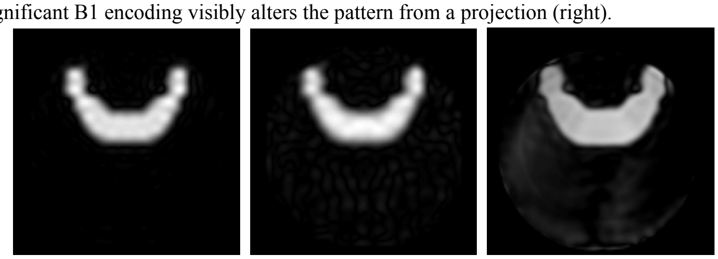

Fig. 4: Simulation addition images of fully sampled excitation (left, 50 segments), accelerated excitation (middle, 12 segments) and experimental verification (right, 50 segments) using a large tip angle optimized set of pulses. The flat profile of the pattern indicates an effective flip angle very close to 90°.

Results and Discussion

As is demonstrated in Figs. 3 and 4, the maximum available transverse magnetization can be excited in the experiment with no limitation on adding the signals of multiple excitations. Fig. 3 shows the single segment excitations in B_1-shimmed mode (50 segments) and PEX (12 segments). In the latter case of 4-fold acceleration by reduction of radial encodings as depicted in Fig. 1 (left), the measurement time is decreased. Furthermore, the single segment excitations are no longer simple projections as illustrated in Fig 3. The method is especially useful for trajectories that require similar RF amplitude for each segment (e.g., segmented radial as opposed to segmented echo-planar), to prevent a particular segment from limiting the others when scaling M_s. Although the optimal control design step is computationally expensive, in the presented technique it is directly parallelizable, therefore its total duration on a machine with a sufficient number of cores is given by the longest single segment optimization time.

Conclusion and Outlook

An RF pulse design algorithm for large tip angle excitation, segmented across multiple repetitions, has been demonstrated in simulations and phantom experiments using parallel transmit acceleration. The technique is beneficial when very short pulse durations are needed as, e.g., in MR spectroscopy. Further investigations are planned to examine properties of different trajectories and segmentation strategies as well as performance in experiments.

References [1] J. T. Schneider et al., Proc. ISMRM, p2601 (2009). [2] J. T. Schneider et al., Proc. ISMRM, p4606 (2009). [3] W. Grissom et al., MRM **56**, 620 (2006). [4] M. Haas et al., Proc. ISMRM, p2589 (2009). [5] U. Katscher et al., Magn Reson Med **49**, 144 (2003). [6] Y. Zhu, Magn Reson Med **51**, 775 (2004). [7] P. Ullmann et al., MRM **54**, 994 (2005). [8] Q. Qin et al., Magn Reson Med **58,** 19 (2007). [9] H.-P. Fautz et al., Proc ISMRM, p1247 (2008). [10] D. Xu, MRM **59**, 547 (2008).

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