A Spatial Domain Method for the Design of RF Pulses in Multi-Coil Parallel Excitation

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INTRODUCTION: To date, all methods for the design of RF pulses in parallel excitation (1,2,3) make use of the linear small-tip-angle approximation (4). As pulses designed using these methods are scaled to produce large tip angles, it is expected that the non-linearity of the Bloch equation will have a detrimental effect on their excitation accuracy. In this work, we use a spatial-domain method to investigate large-tip-angle performance of parallel excitation. We demonstrate the utility of designing pulses with increased Tikhonov regularization (5) in mitigating this error.

METHODS: Given a desired pattern $\mathbf{m}_{des}$, RF pulses can be designed via:

$$\hat{b}_{full} = \arg\min_{b_{full}} \left\{ \left\| A_{full} b_{full} - m_{des} \right\|_W^2 + \beta \left\| b_{full} \right\|^2 \right\}, \qquad [1]$$

where $\mathbf{b}_{full}$- is a vector containing pulses for each coil, $\mathbf{A}_{full}$ is a system matrix containing Fourier matrices (4) that are weighted in the spatial dimension by each coil's transmit sensitivity, **W** is a matrix containing spatial error weighting that can specify an ROI, and λ is a Tikhonov regularization parameter. Transmit sensitivity patterns were measured using an 8-channel coil array and a phantom, the ROI was defined by thresholding an image of the phantom, and the desired pattern $\mathbf{m}_{des}$ was defined as a rectangular block (figure 2a). The applied k-space trajectory was a spiral and was undersampled in the radial (FOV) direction. We denote *speedup factor* as the ratio of the FOV of $\mathbf{m}_{des}$ to the XFOV of the trajectory. The 'linear class' theory developed in (6) dictates that one of the conditions under which RF pulses designed using the excitation k-space formalism may be scaled to produce large tip angles is that B_1 magnitude must be small compared to gradient B_0 magnitude. We reduced B_1 magnitude in two ways: first, B_1 magnitude was scaled to 1/2 and 1/4 its original value and excitation was performed two and four times along the same trajectory, respectively; second, Tikhonov regularization was increased in Equation (1), resulting in lower integrated and peak RF power. We scaled pulses using a range of scaling factors, and simulated them using a Bloch equation simulator. For each scaling factor *i*, the average tip angle $\overline{\alpha_i}$ over the excited block was calculated and tabulated, and NRMSE was calculated between the excited pattern and a desired pattern that was scaled to $\sin \overline{\alpha_i}$.

RESULTS: A speedup factor of 5 was used in all simulations. Figure 1 plots normalized error versus tip angle for pulses designed using Tikhonov regularization parameters β=0, 10, and 100. Also plotted is error versus tip angle for pulses designed using β=0, where RF magnitude was decreased to 1/2 and 1/4 its original value after design and excitation was performed two and four times, respectively. We see that when RF magnitude is not reduced, excitation error increases dramatically as tip angle increases. In contrast, error is significantly lower at large tip angles when Tikhonov regularization is increased. The optimal choice of regularization depends on the tip angle excited. Excitation error is smallest for the repeated excitation cases, and is nearly flat across the range of tip angles for the 1/4 magnitude case.

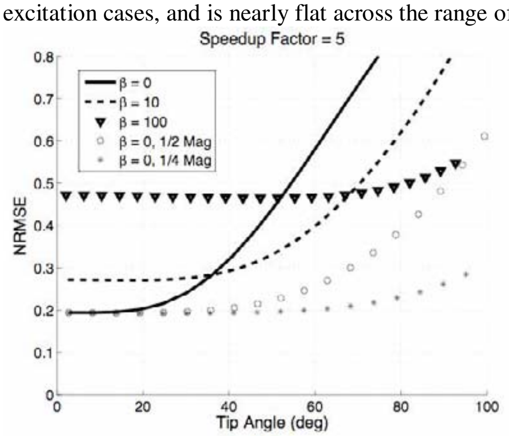

Figure 1: Normalized excitation error (NRMSE) versus tip angle for pulses designed with β=0,10,100 and for pulses with 1/2 and 1/4 magnitude, where excitation was performed two and four times.

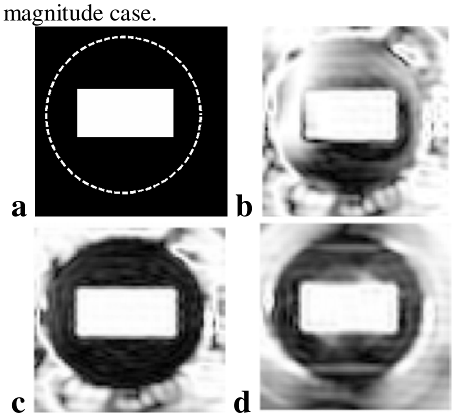

Figure 2: a: Desired excitation pattern. ROI is depicted by dashed circle. **b:** 90° excitation, β=0, NRMSE=0.99. **c:** 90° excitation, 4 excitations at ¼ RF magnitude, NRMSE=0.26. **d:** 90° excitation, β=100, NRMSE=0.53.

DISCUSSION: We have shown that parallel RF pulses designed using the small-tip approximation produce inaccurate excitation at large tip angles. Significant error arises through a violation of one of the conditions laid out by the 'linear class' theory, namely that pulses must have small RF field magnitude compared to gradient field magnitude in order to maintain excitation accuracy at large tip-angles. The violation is the result of sparse excitation k-space coverage in accelerated parallel excitation, and is therefore increasingly problematic as acceleration is increased. Tikhonov regularization may be used to reduce the contribution of large RF magnitude to large-tip-angle error.

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