

Optimization of fast k -space trajectories for 3D spatially selective parallel excitations

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Target audience: RF engineers and MR physicists.

Purpose: A large variety of k -space trajectories have been proposed for use in conjunction with parallel transmission (pTx). Few are capable of achieving true 3D excitations however due to the difficulty of covering transmit k -space in clinically relevant pulse durations (<10 ms), even when using under-sampling. Stack-of-spirals (SOS) and concentric shells (CS) can explore large regions of k -space relatively fast by using the gradient system close to its maximum performance [1,2]. Even with these pulses, it is not clear whether accurate 3D excitations are possible using commonly available clinical gradient systems: A previous study produced high-quality 3.2 ms 3D excitations however using a small animal gradient system with over 10-fold greater slew rate and gradient strength than clinical scanners [3]. Recently, Deniz et al. [4] and Chen et al. [5] have proposed flexible 2D and 3D trajectories defined by control points whose locations were optimized using an orthogonal matching pursuit (OMP) approach. Unfortunately, gradient system constraints were not included in the optimization of the control points positions, yielding highly convoluted and inefficient trajectories. We propose a general optimization framework of both gradients and RF (joint design) that creates very fast, smooth 3D trajectories optimized to the patient and the target excitation pattern. Our trajectories are also defined by control points, but instead of optimizing their individual position we optimize shape parameters of the overall trajectory which reduces the number of sharp turns.

Methods: Pulse calculation: We parameterize our k -space trajectories by shape parameters concatenated in a vector ϕ . In this work, the shape parameters are the extent of the trajectory in k_x , k_y and k_z for its different shells/segments (Fig. 1b) but other global parameters of the trajectory can be optimized as well. Depending on the number of shells/segments, this results in an optimization of 10 to 20 parameters. Our joint design of the gradients and RF waveforms alternately computes the optimal RF pulse (given the previous estimate of the trajectory), and then updates the shape parameters (Fig. 1a). This structure is similar to the methods of Grissom et al. [6] and Yip et al. [7] and is efficient since optimization of the RF pulse is much faster than the optimization of the k -space trajectory (we use a least-squares small flip angle approach for the RF). For the optimization of the shape parameters, we use the Matlab *active-set* algorithm. We compute the Jacobian of the objective function with respect to the shape parameters numerically. For computation of the k -space trajectory given a set of control points and the gradient system specifications, we use a new analytic time-optimal gradient trajectory design approach presented in abstract #3566. Electromagnetic simulation: We tested our approach on simulation data of a 16 channels pTx coil at 7 T [8,9]. To create a more difficult test scenario, only 8 of 16 channels available were used for pulse design (one every other channel).

Results/Conclusion: Fig. 2 shows trajectories and flip-angle maps for a cubic ROI and a brain ROI excited in 3D with and without optimization of the k -space trajectory shape parameters. These results show that high-quality 3D selective excitations can be achieved on clinical systems within 7 ms when the k -space trajectory shape parameters are optimized along with the RF. Moreover, optimization of global shape parameters of k -space trajectories allowed for reduction of the excitation RMSE by factors up to 60%. Run time of the optimization was 2 h for the “cross” trajectory and 3.5 h for the “concentric shells”. We found that robust calculation of the gradients given a set of control points and the gradient system limitations (G_{max} and S_{max}) was crucial in order for the objective function to vary smoothly during optimization (see abstract #3566). Without a robust approach to do so, numerical estimation of the derivatives of the objective function would be widely inaccurate and the overall optimization would not converge. Our approach is applicable to any k -space trajectory, as long as it can be parameterized by global shape parameters.

References: [1] Feinberg et al., Radiology 165(3), 1985; [2] Irrarrazabal et al., MRM 33(5), 2005; [3] Schneider et al., MRM 69(5), 2012 [4] Deniz et al., ISMRM, 2011 [5] Chen et al., ISMRM, 2009 [6] Grissom et al., MRM 68(5), 2012 [7] Yip et al., MRM 58(3), 2007 [8] Wald et al., Magn Reson Med 50(2), 2004 [9] Guérin et al., ISMRM 2013

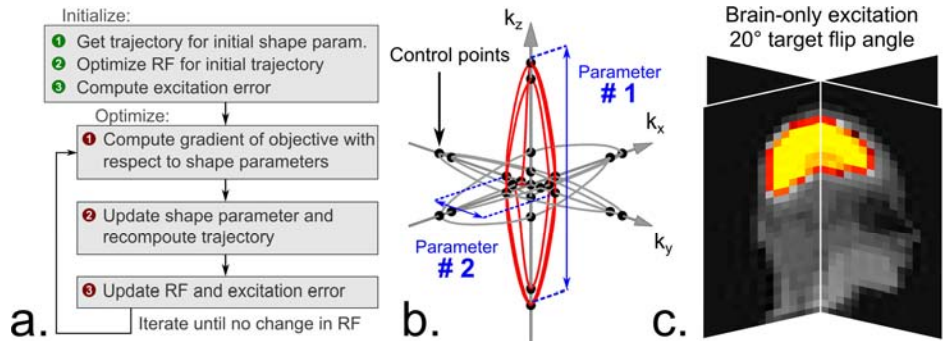


Figure 1: Schematic overview of the trajectory optimization: a) flowchart of procedure, b) example of the 3D Cross trajectory, showing two of the overall six shape parameters, c) target flip angle map, overlaid on the anatomy (brain only 3D excitation target).

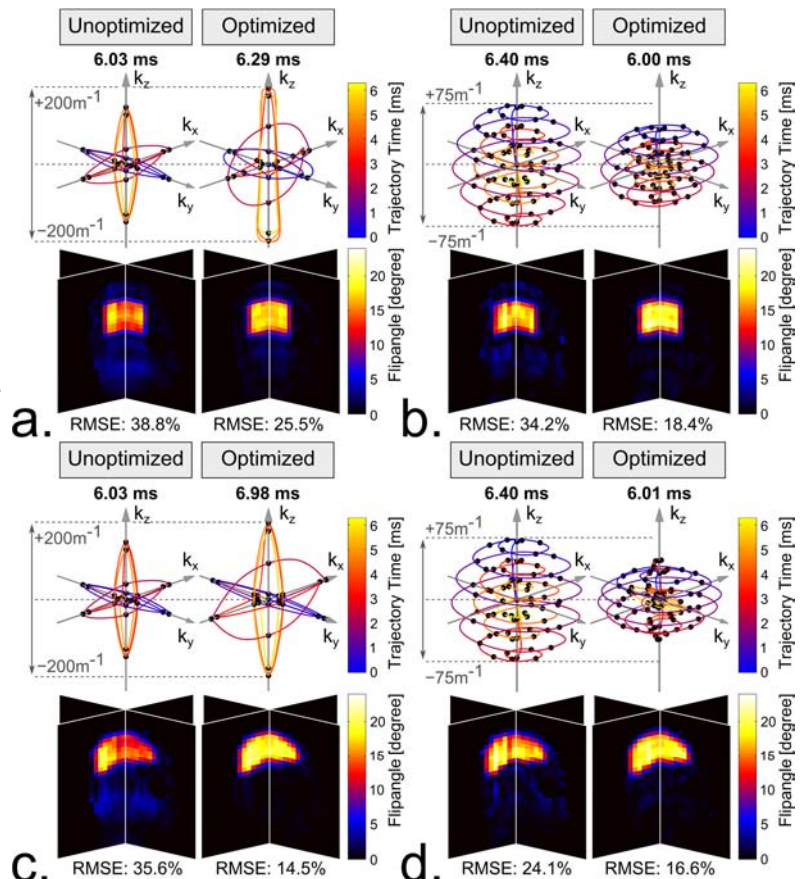


Figure 2: k -space trajectories and flip-angle maps obtained with and without optimization of the trajectory. We show results for two types of trajectories (“cross” in a and c and “concentric shells” in b and d) and two 3D excitation profiles (cubic ROI in a and b, brain ROI in c and d). RF and gradient waveforms were optimized for FOV=20cm, isotropic voxel size 5 mm, $G_{max}=40$ mT/m, $S_{max}=175$ T/m/s.