Ultra-fast inner volume excitations with parallel transmission at 7 Tesla using fully optimized B0-robust k-space trajectories

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Target audience: RF engineers and MR physicists.

Purpose: Three-dimensional radio-frequency excitations (also referred to as inner volume excitations, IVE) in less than 10 ms would be useful for a range of applications including single voxel imaging and skull/fat suppression in spectroscopy. For high quality excitations, the need to traverse high-frequency transmit *k*-space regions usually makes the duration of such pulses prohibitive when using no acceleration (birdcage coil) [1]. Strong gradients and parallel transmission (pTx) can be used to accelerate IVE pulses (in Ref. [2], the authors showed results on a small animal scanner). A recent abstract by Malik et al. showed promising pTx IVE results, however, with pulses on the longer side (i.e., 12 ms), which can be prohibitive for some applications [3]. Previously, we have proposed a framework for the design of ultra-fast *k*-space trajectories for pTx IVE that are fully optimized with respect to the patient' field maps and the target flip-angle [4]. Our trajectories have an optimal shape but remain smooth which allows for using the gradient system at maximum performance (Fig. 2). Here, we report on preliminary experimental evaluation at 7 T of this method and on the improvement of its robustness for *in vivo* situations by incorporation of off-resonance robustness in the design.

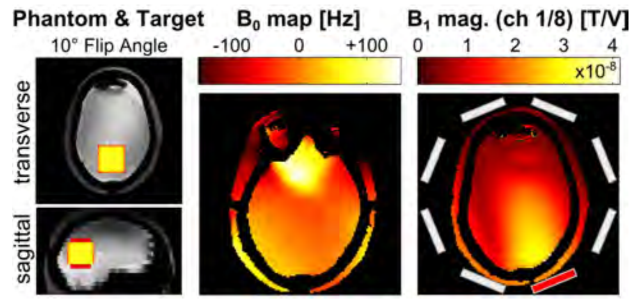

Figure 1: Experimental Setup, left: Head phantom (GRE acquisition, 1.6x1.6x6mm) and target magnetization (4x4x4cm cube, 10° flip angle), center: B_0 map, right: 8-channel pTx system (B_1 magnitude of the first channel is shown).

Methods: *Optimization of k-space Trajectory:* We jointly design ultra-fast *k*-space trajectories along with pTx RF waveforms for excitation of arbitrary 3D shapes. Our method has two main components. First, given a set of control points (black dots in Fig. 2) we find the fastest set of gradient waveforms satisfying the gradient limitations (G_{max} and S_{max}) that connects all the points [5,6]. This method is semi-analytical and we have shown that it is superior to the previously proposed *Optimal Control* approach of Lustig et al. [7]. Second, we optimize the position of the control points from a set of initial positions in transmit *k*-space. A key aspect of the method is that, instead of optimizing the position of the control points individually, we parameterize the overall shape of the cloud of control points using "shape parameters". For 3D shell trajectories (Fig. 2), these are parameters such as the *k*-space extend of the shells in x, y, and z. The shape parameters are fully optimized by the optimizer, which allows fine control of the trajectory while preserving a smooth pathway. For a given set of control points, we design the optimal pTx RF waveform using a Tikhonov least-squares approach. *Experiment:* We evaluated our approach on an 8-channels head 7 Tesla pTx system ("Step 2" pTx, Magnetom 7 T, Siemens, Erlangen) loaded with a realistic 3D-printed head phantom with three compartments (bone, brain and everything else). We incorporate off-resonance robustness in the joint RF/gradient design by enforcing realization of the target flip angle map at offset frequencies –50 Hz, 0 Hz, +50 Hz [8,9].

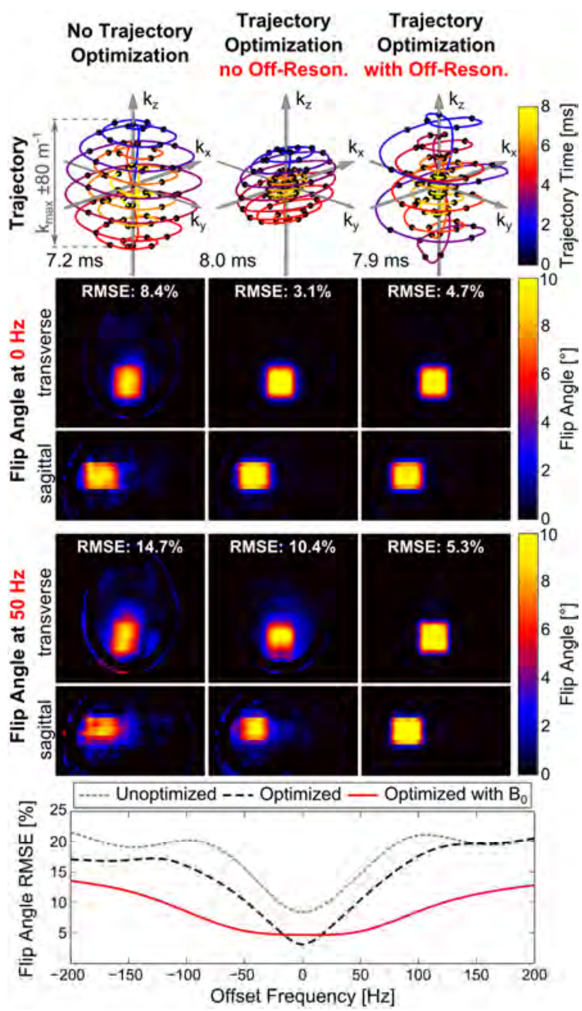

Figure 2: Trajectories (1st row) and flip angle maps with 0 Hz and +50 Hz off-resonance (2nd/3rd row). We show an unoptimized uniform trajectory (left column) and trajectories after shape optimization without and with off-resonance enforcement (center and right column). Gradient constraints: G_{max} = 40 mT/m, S_{max} = 150 T/m/s.

Results: Fig. 2 shows the trajectory before (1st column) and after shape optimization *without* (2nd columns) and *with* enhanced off-resonance robustness (3rd column). It is interesting to note that the optimal trajectory shape is very different when enforcing B_0-robustness than without. The specific optimal shape of these trajectories is not very intuitive, which emphasizes the need for numerical optimization of the control point positions (enforcing off-resonance robustness promotes the optimizer to compress the central shells and decrease the sampling density of the outer shells, 3rd column). Although the optimized trajectory without B_0-robustness performed well at 0 Hz, inclusion of B_0 constraints at ±50 Hz improved realization of the target flip-angle at off-resonance frequencies (Fig. 2). Fig. 3 shows measured GRE maps on our 7 T 8-channel pTx system confirming the benefit of optimizing the *k*-space trajectory, especially when B_0-robustness is included. We envision the design of tailored *k*-space trajectories for a variety of applications requiring an optimal tradeoff between pulse duration, excitation fidelity and off-resonance robustness.

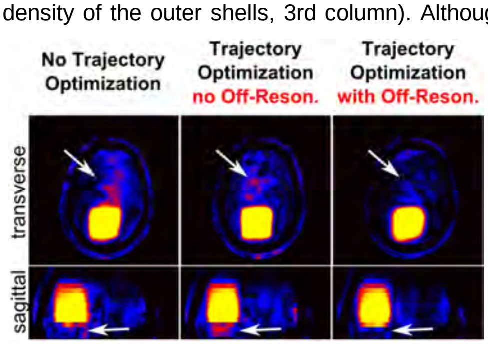

Figure 3: Measured cube excitation using 8-channels at 7T based the unoptimized (left) as well as optimized *k*-space trajectories *without* (center) and *with* (right) enhanced off-resonance robustness.

References: [1] Stenger et al., MRM 44(4), 2000; [2] Schneider et al., MRM 69(5), 2012; [3] Malik et al., ISMRM 2014; [4] Davids et al., ISMRM 2014; [5] Davids et al., ISMRM 2014; [6] Davids et al., IEEE TMI, in press, 2014; [7] Lustig et al., IEEE TMI 27(6), 2008; [8] Grissom et al., MRM 56(3) 2006; [9] Setsompop et al., MRM 61(2), 2009

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