Joint Design of Continuous Excitation k-space Trajectory and RF pulse for 3D Tailored Excitation

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Introduction: In 3D tailored RF pulse design, one typically predetermines a k-space (gradient) trajectory and then designs the corresponding RF waveforms for a target excitation pattern. Recently, the KT-points method [1] was proposed as an approach for jointly designing the trajectory and RF pulses for 3D flip-angle homogenization (B1 shimming). KT-points models the 3D pulse design as a sparse approximation problem and selects sparse phase encoding locations by either a greedy approach or a simple inverse Fourier transform ignoring transmit coil sensitivity and field inhomogeneity. However, with only a few discrete phase encoding locations, it is difficult to approximate a non-smooth target excitation pattern in 3D. Also, it is relatively inefficient to traverse 3D k-space by discrete gradient blips with no RF transmission along those blips. In this work, we extend the KT-points method to a continuous trajectory and jointly optimize the RF waveform by: (1) applying local minimization to further optimize those KT points, and (2) efficiently order those points and generate a fast gradient waveform to traverse those points. We evaluate our proposed joint design with and without local minimization, and compare them with a recently proposed continuous nonselective spiral (SPINS) trajectory [2] for 3D cubic excitation.

Theory: We first determine KT-points locations using a modified orthogonal matching pursuit (OMP) algorithm [3]. The advantage of this approach is we can model the region of interest and transmit sensitivity in the system matrix, generalizing easily to parallel excitation. Then, we use those KT-points to initialize the following joint minimization problem: $argmin_{\boldsymbol{k},\boldsymbol{b}}\ ||\boldsymbol{A}(\boldsymbol{k})\boldsymbol{b}-\boldsymbol{d}||_2$, where $\mathbf{A}(\mathbf{k})$ is a N_p by N_k tall small-tip-approximation matrix [4] (N_p is the number of pixels in the imaging domain, N_k is the number of KT-points, and **k** is a vector containing the discrete KT-points, not the actual continuous waveform k(t)). **b** is the discrete weights corresponding to each KT-point, and **d** is the desired excitation pattern. We alternatively optimize over **k** and **b**. Because N_k is relatively small, the update of **b** can be computed analytically: $\boldsymbol{b} = (\boldsymbol{A}^H\boldsymbol{A})^{-1}\boldsymbol{A}^H\boldsymbol{d}$. For the update of **k**, we run 20 iterations of the Levenberg-Marquardt method [5]. Then we sort those optimized N_k points by a genetic algorithm for the traveling salesman problem. After that, we apply the algorithm introduced in [6] to generate the gradient waveforms to transverse those points in the optimized order and form a continuous k-space trajectory k(t). Finally we generate the corresponding RF waveforms b(t) using the iterative solver from [7].

Method: We implemented our algorithm and ran Bloch Simulation in MATLAB, and we tested our waveforms in a gel phantom using a GE MR750 3.0T scanner with quadrature head coil excitation. We designed a pulse to excite a 6 x 6 x 5 cm^3 cube with 10 degree flip angle. We used $N_k = 65$ in the design, which resulted in a 3.8 ms pulse. The total calculation takes less than 1 minute on an Intel Xeon 3.3.GHz desktop. The actual k-space trajectory was measured for x, y, z directions individually and compared with the design. We compared our method with a predetermined (non-joint) design using a 4.5 ms SPINS trajectory (see Fig.1-a), with the corresponding gradient waveforms generated using the fastest gradient approach as well [6].

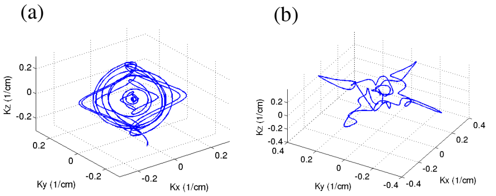

Figure 1: (a) Nonselective spiral (SPINS) trajectory. (b) Output trajectory in the proposed joint design for the cube excitation. The proposed joint design selective traverses regions in the k-space that need high energy deposition.

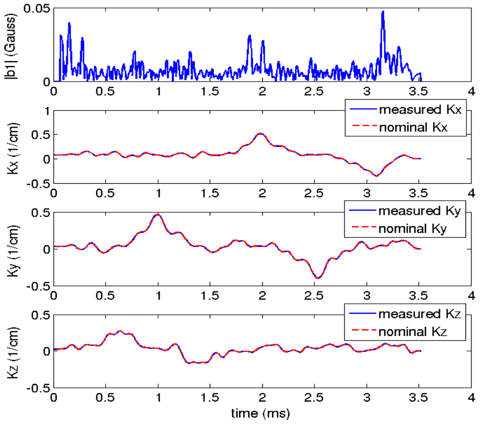

Figure 2: An example pulse waveform generated using projected approach. Note that the actual k-space trajectory follows well with the nominal one, indicating eddy current is not a problem for our design on our scanner.

Results: Figure 1-b shows the 3D trajectory of the proposed design, note that it selectively traverses the k space to deposit energy. The measured trajectory agrees well with nominal trajectories (Fig. 2), indicating that eddy currents may not be a problem for our implementation. Figure 3 shows Bloch simulation and experimental results in 10 slices spanning 24x24x20 cm^3 FOV. Both joint design methods generate less excitation error than the SPINS trajectory, and adding local minimization reduces the NRMSE by 10 % compared with the design without local minimization. Other target patterns were also simulated, showing similar results (not shown).

Discussion and Conclusions: We extended the KT-points method to a joint design of continuous trajectory and RF pulse for 3D tailored excitation, which is capable of exciting a non-smooth pattern with a short RF pulse. In the future, we plan to extend this work to parallel excitation.

[1] Cloos et al, MRM 2012; [2] Malik et al, MRM 2012 [3] Yoon et al, MRM 2012; [4] Pauly et al, MRM 1989; [5] Press et.al, Numerical Recipes in C, 2^{nd} edition P 683, [6] Varizi et al, ISBI 2013, [7] Yip et al, MRM 2006. This work was supported by NIH Grants R21EB012674 and R01NS058576.

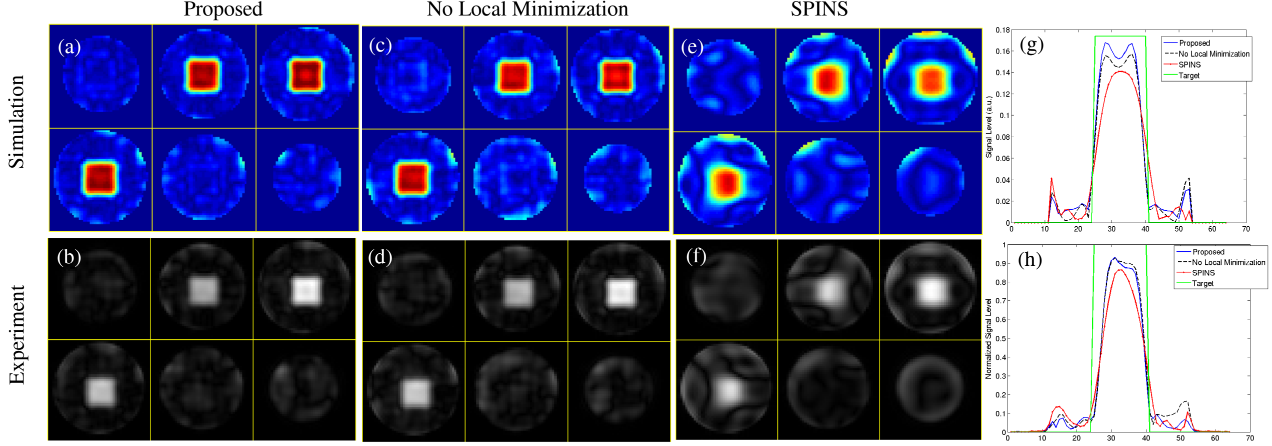

Figure 3: Comparison between proposed joint designs and design using predefined SPINS trajectory: simulation and experimental result of proposed joint design (a, b); joint design without local minimization (c, d); SPINS trajectory (e, f). Both joint design methods achieve higher excitation accuracy than SPINS (NRMSE: 0.15/0.17 vs 0.21) with a shorter pulse length, and adding local minimization reduces the NRMSE by 10% compared with the design without local minimization. Line profiles are drawn along the middle horizontal line in the center slice in both simulation (g) and experimental results (h).