Sparse Parallel Transmit Excitation Trajectory Design for Rapid Inner-Volume Excitation

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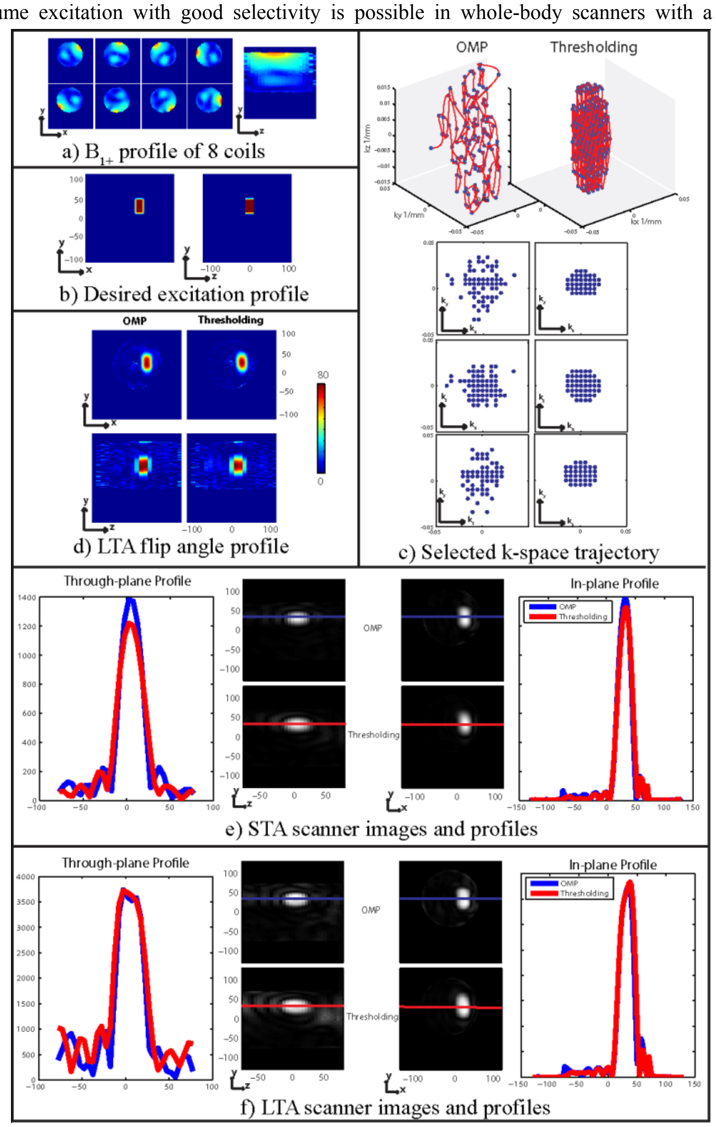
Introduction:

Tailored inner-volume excitation presents many challenges on whole-body MRI systems, such as gradient limitations, the selection of robust excitation k-space trajectories, and transmit field inhomogeneity on high field systems. Parallel transmission enables pulse designers to utilize multiple transmit coils to tailor MR excitations which can result in practical RF pulse lengths and improved transmit field homogeneity [1]. Several approaches have been used to select the excitation k-space locations for 3D excitations [2,3,4,5]. In this work, the modified Orthogonal Matching Pursuit (OMP) method [4] is used to select the k-space locations of greatest importance for sparse parallel transmit 3D pulse design in both small-tip-angle (STA) and large-tip-angle (LTA) regimes. This method is compared to a single-step thresholding approach. Simulations and experimental results show that inner-volume excitation with good selectivity is possible in whole-body scanners with a reasonable RF pulse length.

Methods:

Experiments were performed on a Siemens whole body 7 T Magnetom scanner (Erlangen, Germany) equipped with an eight-channel parallel transmit system. An eight-channel custom-built stripline coil array with elements disposed around the circumference of a 27.9cm-diameter cylinder was used for RF excitation and reception Measurements were performed on a 7.3-L cylindrical water phantom with 15 cm diameter containing 1.25mg/L $NiSO_4.6H_2O$ and 4mg/L NaCl. Multi-slice B_{1+} calibration was performed following the method provided in [6]. ΔB_0 was measured using the phase information of two GRE images with different TE values (TE_1, TE_2 = 5.10, 4.08 ms) and was incorporated into RF pulse design to compensate for phase accrual due to main magnetic field inhomogeneity.

Experimentally measured multi-slice flip angle maps (Fig. 1a) were used to compare the excitation results of two k-space selection algorithms in simulations. Excitation k-space locations were selected using both modified OMP and one-step thresholding methods on a undersampled Cartesian 3D k-space. Undersampling the k-space by a factor of two helped both algorithms extend coverage of the outer regions of excitation k-space. Determination of the time-ordered k-space trajectory was achieved by connecting the selected locations either in a suboptimal EPI-like manner or with selection of the shortest path using a genetic algorithm [7] on a modified travelling salesman problem. The gradient waveforms were then designed for the chosen k-space trajectories based on Ref [8] with gradient constraints of 40mT/m and 120mT/m/s. After gradient waveform design, the pulse with shortest length was chosen from two k-space trajectory options. By varying the number of selected k-space points, the RF pulse lengths of OMP and thresholding approaches were matched. Using time-aligned gradient waveforms and a target 20° (STA) in-plane smoothed rectangular box flip angle profile (Fig. 1b), parallel RF pulses waveforms were designed with the regularized spatial domain method [9]. In addition, the additive angle method [10] was used to design 90° (LTA) excitation pulses for the calculated gradient waveforms. Using Bloch equation simulations, excitation profiles of both designs were compared using normalized root mean square error (NRMSE) of the magnetization and RMSE of the flip angle for STA and LTA designs, respectively. Designed 3D parallel transmission RF waveforms were played out on the scanner and flip angle measurements were obtained. In addition to flip angle maps, 3D spoiled gradient echo images were acquired to compare excitation fidelity.



Results and Discussion:

Designed k-space trajectories for OMP and the thresholding method are shown in Fig. 1c. Blue dots represent the selected k-space locations and red lines represent the k-space trajectory obeying the system maximum gradient and slew rates. 120 and 200 k-space locations were selected to approximately match the modified OMP (8.78ms) and one-step thresholding (8.65ms) RF pulse lengths. These pulses correspond to ~35 times reduction of the fully sampled 3D Cartesian k-space trajectory length. Use of OMP for selection of the k-space locations resulted in coverage of a larger extent of k-space compared to basic thresholding (Fig. 1c). According to the Bloch simulations, the extension of k-space coverage achieved with the OMP method resulted in reduced error: NRMSE/RMSE error = 0.011/0.26 (OMP), 0.013/0.34 (thresholding). The in-plane and through-plane experimental MR signal profiles obtained from OMP versus the one-step thresholding algorithm are shown in Fig 1e and Fig. 1f for STA and LTA, respectively. Calculation time to determine k-space locations was greater for the OMP algorithm since the duration of each sparsifying iteration is approximately equivalent to the overall duration of the one-step thresholding approach. Improved STA excitation fidelity was also associated with a slight increase in net power deposition (~0.9W for OMP compared to ~0.8W for thresholding). However, the power deposition behavior was reversed for the LTA case:~34W for OMP and ~47W for thresholding. This behavior can be attributed to the additive angle method which may favor good agreement between the desired and designed profiles, which is valid for OMP designs with higher resemblance to the desired profile.

In conclusion, inner-volume excitations were demonstrated with reasonable RF excitation pulse lengths on a whole-body 7T scanner. Both OMP and thresholding k-space selection algorithms generated acceptable excitation profiles with significantly reduced excitation pulse lengths beyond the limits of conventional parallel transmission. OMP profiles were better matched to the desired profile, with the possibility of reduced power in the LTA regime.

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