2-spoke placement optimization under explicit SAR and power constraints in parallel transmission at ultra-high field

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Target Audience: High Field MRI physicists/engineers involved in RF pulse design, particularly in the framework of parallel transmission (pTx)

Purpose: The spokes method[1] combined with parallel transmission is a promising technique to mitigate the B_1^+ inhomogeneity at ultra-high field in 2D selective excitations. To date however, the spokes placement optimization[2-5] for the Magnitude Least Squares (MLS) pulse design problem[6] has never been done in direct conjunction with the explicit SAR and hardware constraints. In this work, the optimization of 2-spoke trajectories and RF-waveforms is performed under these constraints explicitly and for axial slices of the human brain at 7T. The problem first is considerably simplified by making the observation that only the vector between the 2 spokes is relevant for the MLS cost-function, thereby reducing the size of the parameter space and allowing a more exhaustive search. The algorithm starts from a set of initial k-space candidates distributed on a Cartesian grid and performs in parallel for all of them simultaneous optimizations of both the RF waveforms and the k-space locations, under strict SAR and power constraints. Bloch simulations and in-vivo T_2*-weighted images acquired at 7 T validate the approach.

Materials and Method: For 2-spoke designs, the MLS cost function in the small tip angle approximation is sensitive only to the 2-component vector between the 2 spokes: $\mathbf{FA(r)} = \left|\mathbf{FA_1(r)e^{-i(k_{1,x}x+k_{1,y}y)}} + \mathbf{FA_2(r)e^{-i(k_{2,x}x+k_{2,y}y)}}\right| = \left|\mathbf{FA_1(r)} + \mathbf{FA_2(r)e^{-i(\Delta k_x x+\Delta k_y y)}}\right|$, where FA_1 and FA_2 are the two complex flip angles (FA) generated by the two RF sub-pulses respectively, and $(\Delta k_x,\Delta k_y)$ are the components of the vector between the two spokes. The parameter space for the 2-spoke placement and MLS problem therefore is 2 (i.e. Δk_x and Δk_y) (2(N-1) dimensional for N spokes), the first spoke being placed at the origin (0,0) and the second one at $(\Delta k_x,\Delta k_y)$ with no loss of generality. As a first step, the $(\Delta k_x,\Delta k_y)$ parameter space was discretized uniformly over the interval $[-3;3]\times 2\pi/FOX$ (FOX = 25 cm) with 11 steps in each direction. The MLS pulse design problem under strict SAR and power (peak and average) constraints was solved using the active-set (A-S) algorithm[7] in parallel for all initial $(\Delta k_x,\Delta k_y)$ points in k-space, with $B_1/\Delta B_0$ maps acquired at 7T for four different subjects, and for a target FA of 22°. For each independent optimization, both the spokes-weights and the $(\Delta k_x,\Delta k_y)$ values were free to evolve (according to the A-S rules) simultaneously so that the vicinity of each initial location could be explored. For SAR constraint calculations, $Q_{10g}(r)$ and Q_G matrices for the 10-g SAR at location r and the global SAR respectively were compressed according to the virtual observation points algorithm[8]. Overall, this yielded for each subject a total of 121 independent optimizations distributed on the 16 cores of a Xeon-E5-2670 bi-processor computer using the Matlab parallel computing toolbox (The Mathworks, Natick, MA, USA). For both RF transmission and reception, a home-made 8-channel transceiver-array head coil was used. The transmit sensitivity profiles were acquired on the entire brain with a multi-slice magnetization-prepared turbo-FLASH sequence (resolution: 5 mm isotropic, total acquisition time: 4 min)[9]. The ΔB_0 map and high-resolution mask of the brain were independently acquired with fast multi-slice multiple-echo GRE sequences. The spokes-placement and RF pulse design was validated using T_2*-weighted sequences (FA = 22°, TR = 400 ms, TE = 27 ms, resolution = $0.5 \times 0.5 \times 6$ mm^3) in the CP and the proposed 2-spoke configurations, as well as with Bloch simulations in the CP, RF-shim and 2-spoke modes for slices at the isocenter of the magnet.

Results and discussion: The 121 independent optimizations under strict SAR and power constraints could be performed in 14 seconds. Fig.1 reports the flip angles obtained with Bloch simulations for the CP, RF-shim and proposed 2-spoke modes respectively. The corresponding NRMSEs are also provided. A NRMSE less than 2 % was systematically returned for all 4 subjects in the 2-spoke configuration, providing evidence for certain robustness with respect to subject, slice placement and B_0 shim. CP modes and RF shims on the other hand returned 16-18 % and 4-8 % respectively. Fig.2 shows the T_2*-weighted images for subject #4 for the CP and 2-spoke modes. The method is applicable for a higher number of spokes, although the dimensionality of the resulting parameter space would make such an exhaustive search more difficult. However, as shown here and in[10], 2-spoke pulses seem to be enough to obtain excellent 2D excitation uniformity for human brain applications at 7T and 9.4T.

Conclusion: A simple and fast algorithm for 2-spoke' placement in parallel transmission under explicit SAR and power constraints was reported, where less than 2 % NRMSE for the MLS problem could be systematically obtained at 7T over an axial slice of the human brain, and in about 14 s. To the extent of the four subjects tested in this study, the approach reveals itself to be fast and robust with respect to different experimental conditions (subject, slice placement, shim).

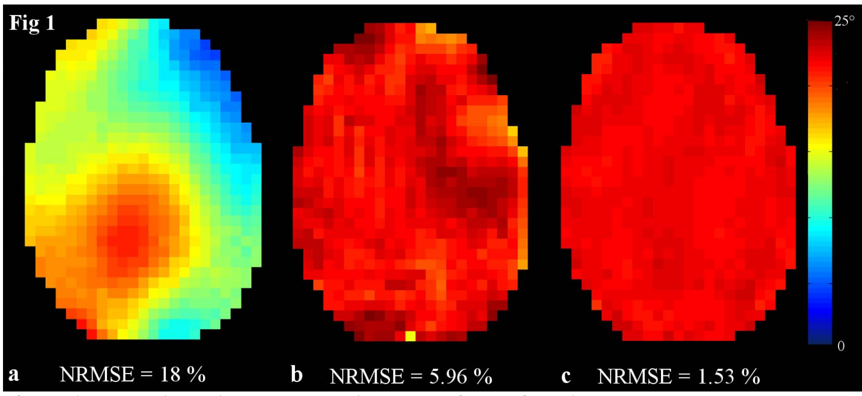

Figure 1: Bloch simulations corresponding to the (from left to right) CP, RF shim and 2-spoke mode for subject # 4.

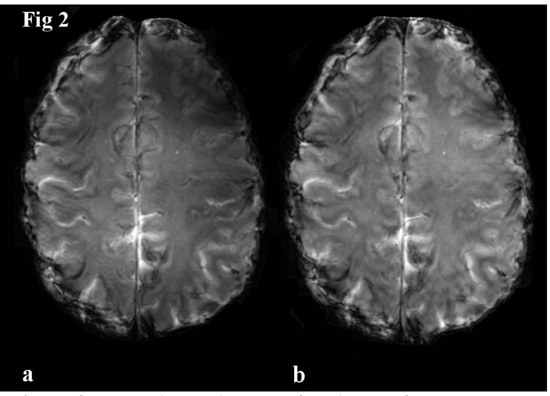

Figure 2: T_2* weighted images of subject #4 for the a) CP and b) 2-spoke configuration.

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