Influence of 2-spoke pulses k-space placement in different optimization strategies and cost functions

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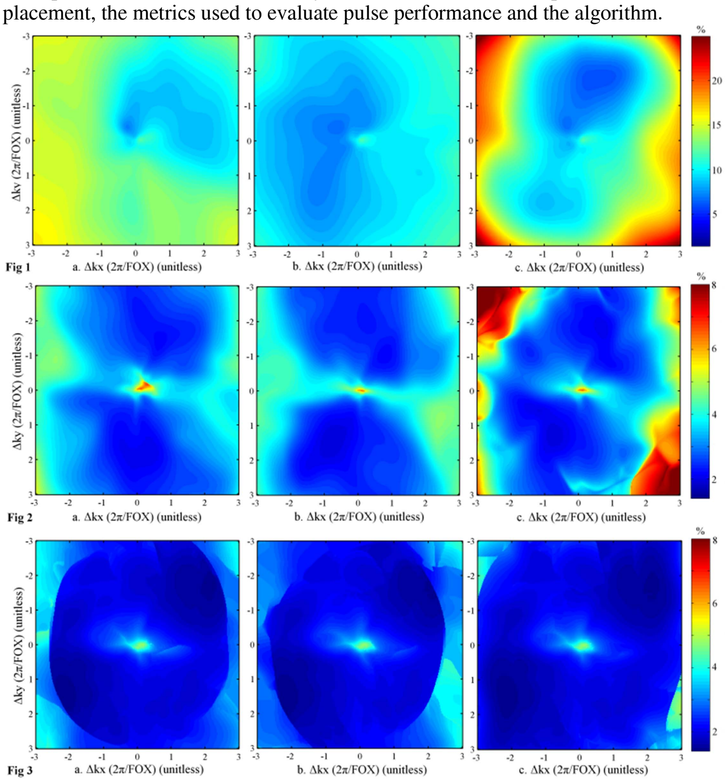
Target Audience: High Field MRI physicists/engineers involved in RF pulse design, particularly in the framework of parallel transmission (pTx)

Purpose: Two-spoke parallel transmission pulses have been shown to be powerful to mitigate B_1^+ inhomogeneity in 2D at fields up to 9.4T in the human brain[1], and spokes k-space placement often has been suggested to be critical for good performance[2-5]. In this work, we explore the impact of this placement for different pulse performance metrics, i.e. the Magnitude Least Squares (MLS) and Least Squares (LS) cost functions, and different algorithms: the Active-Set[6] (AS) and the Variable-Exchange[7] (VE) methods. Surprisingly, the normalized root mean square error (NRMSE) in the case of the MLS problem and the AS algorithm remains excellent and robust in large regions of k-space.

Materials and Methods: 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)[8] and using a 7 T Magnetom scanner (Siemens Healthcare, Erlangen, Germany). The ΔB_0 map and high-resolution mask of the brain were independently acquired with fast multi-slice multiple-echo GRE sequences. The target flip angle (FA) for pulse design was 22° (TR=400 ms) over the axial slice located at the magnet isocenter. 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: $\mathbf{FA(x,y)} = \left|\mathbf{FA_1(x,y)e^{-i(k_{1,x}x+k_{1,y}y)}} + \mathbf{FA_2(x,y)e^{-i(k_{2,x}x+k_{2,y}y)}}\right| = \left|\mathbf{FA_1(x,y)} + \mathbf{FA_2(x,y)e^{-i(\Delta k_x x+\Delta k_y y)}}\right|$, where FA_1 and FA_2 are the two complex FAs generated by the two RF sub-pulses respectively, and (Δk_x, Δk_y) are the components of the vector between the two spokes. Thus an algorithm such as A-S, making use only of the MLS cost-function and its derivatives[6] should only be sensitive to this vector (provided the initialization is also independent of the absolute spokes placement). The VE method on the other hand, although designed to solve the MLS problem, uses the phase of the excited pattern to iterate[7] and therefore should be more sensitive to the absolute spokes placement. Finally, the LS problem is evidently very dependent on this placement[2-5]. In this study, the distances Δk_x and Δk_y hence were varied systematically over the interval [-3;3]×2π/FOX (FOX = 25 cm) with 300 steps in each direction. For each $\mathbf{\Delta k}$ vector, three k-space configurations were tested: first spoke at (0,0) and second at (Δk_x,Δk_y), first spoke at (-Δk_x,-Δk_y) and second spoke at (0,0), and 2 spokes located symmetrically around the origin. In each case, the following problems were solved by using Matlab (The Mathworks, Natick, MA, USA): 1) LS problem (CP mode target phase) with AS (also with SAR and power constraints), 2) MLS problem with VE only (with the CP mode phase pattern and a Tikhonov parameter equal to 0) and 3) MLS problem with AS (initialized by VE) (with strict SAR and power constraints[6]), thereby investigating the dependence of the flip angle NRMSE on the 2-spoke' placement, the metrics used to evaluate pulse performance and the algorithm.



Results and Discussion: Fig.1 represents the landscape of the NRMSE in the (Δk_x,Δk_y) plane for the LS-AS configuration for the 3 trajectories and for subject #4. In agreement with [2-5], Fig.1 confirms that the NRMSE for the LS problem is sensitive to the absolute placement of the 2 spokes. When the VE method is employed to solve the MLS problem, Fig.2 shows a good performance in some regions (NRMSEs vary between 2 and 10 %) but definitely an inferior robustness with respect to spokes absolute placement, and inferior performance compared to the MLS-AS combination as seen in Fig.3. While there is a slight variability in the three different cases in the corners of k-space, in general the AS algorithm appears to be robust with respect to the absolute spokes placement (in agreement with [6]). The MLS-AS (Fig.3) configuration appears only sensitive to the distance between the two spokes. Moreover, the final NRMSE is excellent in significantly large portions of the parameter space, achieving 1.5 % and 5 % for the best and worst configurations respectively. Similar trends were observed for the other subjects and for different slice placements. For B_1 and ΔB_0 maps acquired on 4 healthy subjects at 7T, RF pulse performance is demonstrated to be barely dependent on the 2-spoke trajectory for the MLS-AS combination in a large region of k-space.

Figures: The NRMSE value obtained from in-vivo B_1 and ΔB_0 data for each (Δk_x, Δk_y) pair and with the following metrics, algorithms and trajectories:
Fig.1 LS-AS for a) (0,0) and (Δk_x, Δk_y) b) (-Δk_x, -Δk_y) and (0,0) c) 2-spokes located symmetrically around the origin.
Fig.2 MLS-VE for a) (0,0) and (Δk_x, Δk_y) b) (-Δk_x, -Δk_y) and (0,0) c) 2-spokes located symmetrically around the origin.
Fig.3 MLS-AS for a) (0,0) and (Δk_x, Δk_y) b) (-Δk_x, -Δk_y) and (0,0) c) 2-spokes located symmetrically around the origin.

Conclusion: For 2-spoke configurations for brain imaging at 7 Tesla, in the case of the MLS problem combined with the AS algorithm, first our results confirm that RF pulse performance only depends on the distance between the two spokes (but can vary slightly depending on the initialization), thereby allowing for a more thorough search in parameter space to possibly reach global optimality. Moreover, the best NRMSE seems to be only sensitive to the magnitude of that vector. Finally, given the robustness of the pulse performance with respect to k-space placement in the same scenario, attempts to solve this particular problem can be made at only a few particular k-space locations to find excellent RF pulse candidates with high probability.

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