Magnitude-Constrained Spokes Design for B_1^+ Inhomogeneity Correction

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Introduction

Over the past decade methodological breakthroughs as well as solid technical engineering work have introduced 3 tesla high field MR into clinical practice. Nevertheless, high field systems still pose challenges in terms of RF excitation uniformity (i.e., RF-shading) and specific absorption rate (SAR) limitations. In particular, RF wave interference effects can lead to inconsistent contrast behaviour and in extreme cases even to complete signal cancellation. From the intrinsic subject dependence of RF shading it is clear that coil-only based approaches principally cannot solve this problem for the general case [1,2]. Recently introduced parallel transmit technologies with enhanced control over the excitation process are considered as one potential solution for these problems. Two different flavours of parallel transmit are distinguished: 1) static RF-shimming: In this case each transmit pathway has the flexibility to add a complex weighting to an otherwise constant RF waveform [3]. 2) dynamic RF shimming (full parallel transmit) with so-called spokes trajectory RF pulses [4,5]. Here each transmit path has its own fully independent RF-excitation capability. In this work, a novel parallel transmit spokes pulse design framework based on a magnitude-constrained design is introduced. Simulations and phantom measurements performed at 3T show significantly improved excitation profile uniformity.

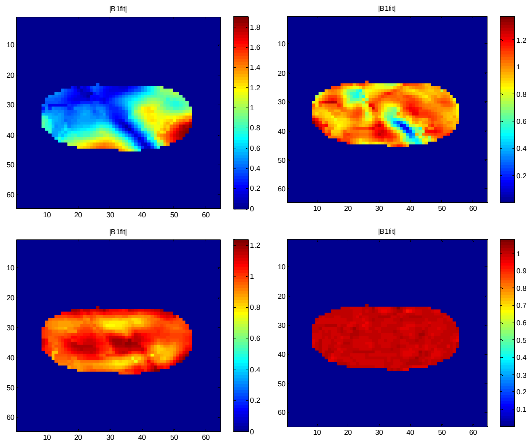

Fig. 1: Simulations results on measured B_1 maps. The left and right side shows one and four spokes, respectively. The top row depicts the traditional, phase and magnitude constrained design, while to bottom row the new magnitude-constrained approach.

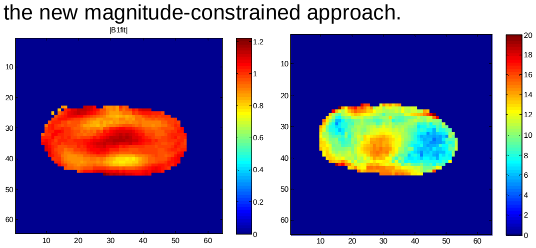

Fig. 2: Predicted (left) and measured profile (right; in units of degrees).

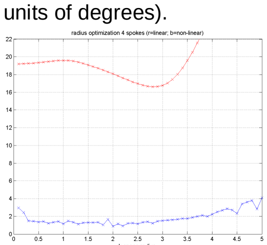

Fig. 3: Spokes placement for the magnitude and phase (red line) and magnitude-constrained design (blue line).

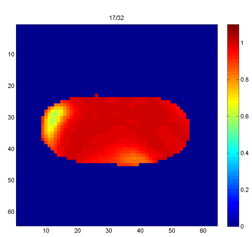

Fig. 4: Large-tip angle excitation solved with the Bloch equations. Only few spots show a decreased homogeneity.

Theory and Methods

The spokes sequence consists of in-plane excitation pulses (z) and a few points in k_x-k_y to improve through-plane homogeneity. In the small-tip angle approximation, the pulse problem separates into an in-plane and a through-plane sub-problem. Any excitation pulse can be used in z. Here, we design one with the SLR transformation, which is equivalent to the Fourier transformation in the small-tip angle regime. The matrix describing the 2D in-plane excitation problem is given by

$$\mathrm{T}_{\rho,(\gamma,\kappa)} = e^{2\pi i k_\kappa r_\rho} s_\gamma(r_\rho) e^{2\pi i f_0(r_\rho) t_\kappa},$$

where k_κ denotes the excitation k-space position of the κ^{th} spoke, r_ρ the position of the ρ^{th} voxel in (x, y), $s_\gamma(r_\rho)$ the complex transmit sensitivity of coil γ, $f_0(r_\rho)$ the B_0 off-resonance (in Hz) and t_κ the time to the middle of a spoke. The last term (with f_0) can be included optionally and corrects the phase additionally induced by B_0 field inhomogeneities. It neglects the $f_0(r_\rho)$ evolution within one sub-pulse of the z direction. The individual weighting coefficients *w* for all coils and spokes are traditionally determined by $\min\|\mathbf{Tw}-1\|_2$, hence constraining both magnitude and phase in x-y to be one. This problem is easily solved by any linear least squares optimisation; here we use the Moore-Penrose pseudo-inverse. Constraining only the magnitude leads in the 2-norm to $\min\|\,|\mathbf{Tw}|-1\|_2$, which amounts to a non-linear least squares optimisation problem. This is solved here with a gradient descent algorithm (Matlab function "fminunc"). A Tikhonov regularisation minimises RF amplitudes and improves experimental robustness. The placement of the spokes was investigated by varying the radius in k-space of four spokes. The optimisation was implemented in Matlab. The spokes pulse design was evaluated by simulations (based on numerical solution of the Bloch equations) and measurements using a multi-cabinet GE Signa Excite 3T parallel transmit system equipped with a 16-channel whole-body transmit TEM array. Both the transmit sensitivity mapping and the evaluation of the spokes excitation pulses were performed based on a 2D gradient echo readout.

Results and Discussion

Simulation results with measured B_1^+ maps (Fig. 1) showed an improvement in homogeneity for one spoke (= static RF shimming) from 49.5% to 18.1% RMS error for the magnitude and phase, and for the magnitude constrained design, respectively. For four spokes, the homogeneity could be improved from 10.0% to 1.4% RMS error, respectively. Fig. 2 shows the measured excitation profile in the torso phantom. The prediction and the measured profiles are similar, confirming a considerably improvement of B_1^+ inhomogeneity. A Gaussian-distributed B_0 off-resonance with a peak of 200Hz in the centre of the FOV was added to the design and could be completely compensated for, leading to a negligible additional error. The placement for four spokes (Fig. 3) was found to be important for the magnitude and phase, but not so crucial for the magnitude-constrained design. As expected, extending the spokes design to the large-tip angle regime introduces some additional error (Fig. 4). However, the 90° excitation profile is astonishingly homogeneous and the through-plane profile is preserved.

Conclusion

Magnitude-constrained spokes pulse design leads to a considerable improvement of B_1^+ homogeneity and/or can shorten the amount of spokes required for a desired homogeneity. The design shows robust results *in vitro* when including B_0 information in the design.

References

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