Mitigate B1+ inhomogeneity by the combination of RF shimming and B1+ remapping using nonlinear gradient coils
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TARGET AUDIENCE
Scientists interested in homogeneous excitation in high field MRI

INTRODUCTION
High-field MRI shows great promise due to its high SNR; Yet one challenge of high-field MRI is the inhomogeneous flip angle distribution when a volume radiofrequency (RF) coil is used for RF excitation. This artifact is due to the increased interaction between the dielectric sample and the transmitted RF fields when $B_1$ is higher than 4T. Different methods for mitigating $B_1+$ inhomogeneity have been proposed, including RF excitation with multiple RF coils using RF shimming 4-7 or parallel RF excitation techniques, like transmit SENSE 8,9. Although effective 10, parallel RF excitation strategies require complex and expensive instrumentation, accurate estimates of phases and amplitudes of the $B_1+$ field for each RF coil, and specific absorption rate (SAR) management 11.

Recently, methods to achieve homogeneous transverse magnetization $m_{xy}$ distribution using linear and quadratic spatial encoding magnetic fields (SEMs) have been proposed 11-12. In recent work, we have proposed spatially selective RF excitation with generalized spatial encoding magnetic fields (SAGS), where a combination of linear and nonlinear SEMs can be used to remap the $B_1+$ map such that the RF pulse can be designed efficiently in a lower dimension in order to achieve a homogeneous $m_{xy}$ distribution 13. In this study we propose a new method of combining RF shimming and SAGS to further improve the flip angle homogeneity. This approach was numerically demonstrated using experimental data.

THEORY AND METHODS
The equation that describes SAGS under the small angle approximation is $M_{xy}(r, T) = \int_0^1 B_1^+\text{exp}[2\pi rf(t) \cdot f(t)] \cdot \text{d}s dt$, where $f(r) = f_1(r), \ldots, f_n(r)$ describe $n$ SEM spatial distributions. $g(t) = [g_1(t), g_2(t)]$ describes the instantaneous strength of each SEM. For a slice-selective (in z-axis) spoke trajectory, $M_{xy}(x, y) = B_1^+(x, y) \sum_{k=1}^{n} \text{exp}(2\pi k \cdot f(x, y))$. Our previous work with SAGS suggested that the target transverse magnetization distribution $m_{xy}$ can be achieved efficiently under realistic $B_1^+(x,y)$ if there exists 1) a one-dimensional function $f(x,y)$ generated by a linear combination of SEMs and 2) a function $M$ such that: $m_{xy}/B_{1\text{shim}}(x,y) = M(f(x,y))$.

Here we propose that, instead of directly designing RF pulses to achieve the target $B_{1\text{shim}}(x,y)$, we may use RF shimming to design RF pulses to another $B_{1\text{shim}}(x,y)$ such that $m_{xy}/B_{1\text{shim}}(x,y)$ can be more accurately approximated by $M(f(x,y))$. Note that here $B_{1\text{shim}}(x,y)$ can be highly spatially inhomogeneous. To design $B_{1\text{shim}}(x,y)$, we parameterized $B_{1\text{shim}}(x,y) = \sum_{p=1}^{n} b_p B_1(x,y)$, $M(f) = \sum_{p=1}^{n} \alpha_p \cos(f) + \beta_p \sin(f)$, and $f(x,y) = \sum_{a=1}^{m} \alpha_a f_a(x,y)$. To achieve homogeneous $m_{xy}$, we optimized $\{a_p, B_1, \alpha, \beta\}$ to minimize $\|1 - B_{1\text{shim}}(x,y) M(f(x,y))\|^2$. We limited this work to the case of a two spoke trajectory, with each spoke having the same amplitude $M(f) = \alpha \cos(f)$. We simulated twenty RF transmit coils uniformly distributed over a uniform spherical phantom with 15 cm radius using a multipole expansion method 16. The FOV was a transverse square section through the center of the sphere, with the side length equal to the sphere’s diameter (image matrix = 32 X 32 voxels). The dielectric constant and the electric conductivity of the sphere were $\epsilon = 52$ and $\sigma = 0.55$ (1/W m), respectively. Phantom and in vivo human head experimental data were acquired using 8 RF transmit coils on a 3T system. All calculations attempted to achieve a homogeneous 10-degree flip angle distribution.

RESULTS
Figure 1 shows $B_1^+$ maps in RF shimming method aiming at achieving a homogeneous $M_{xy}$ distribution (top) and in combined RF shimming and SAGS method aiming at generating $B_1^+$ such that after $B_1^+$ remapping, the $M_{xy}$ distribution becomes the most homogeneous using quadratic SEMs (bottom). Figure 2 shows $M_{xy}$ maps. The $B_1^+$ distribution was relatively homogeneous in the FOV (Figure 1 top) when RF shimming was used directly to reduce $M_{xy}$ variability (Figure 2 top). Using combined RF shimming and SAGS, the $B_1^+$ distribution shows clear smooth spatial variation (Figure 1 bottom). While such a $B_1^+$ distribution was visually suboptimal, when combined with quadratic SEMs, it actually achieved a more homogeneous $M_{xy}$ distribution (Figure 2 bottom). Quantitatively, RF shimming for a homogeneous $M_{xy}$ distribution directly has $\sigma = 6.4\%$, 13.0\%, and 13.2% for simulations, phantom experimental data, and human head imaging data, respectively. Using combined RF shimming and SAGS, we found that $\sigma = 2.8\%$, 8.4\%, and 9.2% for simulations, phantom experimental data, and human head imaging data, respectively.

DISCUSSION
Comparing to results of using RF shimming directly or using previously proposed SAGS method, here we demonstrate that combining SAGS and RF shimming can further improve the homogeneity of flip angle distribution. Such an RF pulse design strategy was specifically demonstrated for high field MRI using simulations based on experimental $B_1^+$ data. We noticed that our results of $M_{xy}$ distributions showed some non-smooth variation, possibly because of inaccurate $B_1^+$ map estimates. The proposed methods uses RF shimming, therefore only one common driving RF amplifier is needed to implement the RF pulse, thus complexity and cost are less than for fully parallel RF excitation. However, quadratic SEMs are needed to implement this method and their current availability is limited.

REFERENCES