Tailored Excitation Using Non-Linear B₀-Shims
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Introduction
In MRI, RF transmission field ($B_1^\text{RF}$) imperfections can lead to undesired spatial variations in image signal-to-noise ratio (SNR) and contrast. This potential problem becomes increasingly apparent at higher field strengths, where the shorter RF wavelengths lead to increasing spatial variations in the amplitude and phase of $B_1^\text{RF}$. The mitigation of this problem is an active area of research, with proposed solutions falling into two categories: homogenization of the amplitude of $B_1^\text{RF}$ ($B_1$ shimming) [1-4], and homogenization of the RF flip angle in the presence of inhomogeneous RF fields (multi-dimensional excitation) [5-7]. In the following we propose a method for the second category that allows reduced pulse duration by employing non-linear gradients. Previous work using radial or PatLoc gradients has demonstrated efficient multi-dimensional excitation for specific shapes of the desired volume [8-10]. Similarly, the use of non-linear gradients may facilitate the use of such pulses for $B_1$ mitigation. To investigate the effectiveness of this approach for imaging the human brain at 7T, we used a combination of linear gradients and non-linear resistive $B_0$ shim coils.

Theory
For pulse sequence shown in Fig. 1, it can be shown that the final flip angle $\theta = \arccos(\cos\alpha_1 \cos\alpha_2 - \cos\phi \sin\alpha_1 \sin\alpha_2)$ for any spatial location, with $\phi$ corresponds to the rotation caused by the shim pulse $S$. If $\alpha_1=\alpha_2$, for any desired excitation $\theta$, $\varphi = \arccos((1 + \cos 2\alpha - 2 \cos\theta)/(1 - \cos 2\theta))$, which can be approximately generated by the shim currents $\phi_\text{shim} = \sum_i \phi_i \sum_j \int S_j(t)dt$ with the time integral running over the pulse interval $\Delta t$ via root-mean-squared based multi-linear regression.

Experiment
Experiments were performed on phantoms and on human brain using a Siemens Magnetom 7T (Erlangen, Germany) whole body scanner based on an Agilent 7T-830-AS (Oxford, UK) shielded magnet design. The system provided 5 second order shims producing $x^2, xy, xz, y^2$ field dependencies with maximum strengths of 1.6kHz/cm². Together with a zero order term (effectuated either through the reference frequency or the RF pulse phase) and the linear gradients, a total of 9 degrees of freedom were available for flip angle optimization. Our $B_0$-based flip angle optimization involved the following steps: 1: Calibration of the fields $c_j$ generated by the individual shim terms on a phantom. 2: Determination of subject-specific distribution of $\alpha$ based on $B_1^\text{RF}$ field mapping using the Bloch-Siegent method [11] using a GE sequence and an 8 ms ±4kHz Fermi-apodized irradiation pulse. 3: Calculation of $\varphi$ by substituting $\alpha$ into the equation above. 4: Shim optimization: It is possible to optimize the uniformity of $\theta$ over a range of sub-pulse amplitudes and choose the amplitude value that leads to the best $\theta$ uniformity or has other favorable attributes, for example minimal sensitivity to temporal variations in $\varphi$ or minimal RF power. Here, the optimization was performed by selecting a non-sub-pulse flip angle $\alpha$ of $10^\circ$, which was close to the expected minimum required for the selected target angle $\theta$ which was set at $20^\circ$, and calculating the desired $B_0$ distribution, followed by a linear least squares optimization of the shim currents to create this distribution. The solution that resulted in the smallest deviation from the desired field was then chosen. 5: Evaluation of the optimized $B_0$ shim distribution $\varphi$ was performed by combining the 2-pulse excitation (Fig.1b) with a GE readout using the following parameters: $\Delta t=1.35$ms, TE=5ms, TR=600ms, 64x64 resolution FOV 27cm, slice thickness 3.5mm. The flip angle $\theta$ was measured by dividing the image from the 2-pulse excitation by the receive coil profile; the latter was derived from a low flip angle GE acquisition after division by the $B_1^\text{RF}$ profile. Simulations were performed to compare the optimized 2-pulse excitation with conventional 2- and 3-pulse pulses that did not apply higher order shims.

Results
In human brain, substantially improved $\theta$ uniformity was achieved using $B_0$ shimming. Fig. 2 shows an example of this for $\theta=20^\circ$; despite the $20^\circ$ r.m.s. variation in $B_1^\text{RF}$ over the slice, the variation in estimated $\theta$ was within 11%. The optimization was performed around $\alpha=0$, with the average $\alpha$ around $10^\circ$. In Fig. 2: (a) sagittal localizer indicating location of axial slice; (b) $B_1^\text{RF}$ amplitude estimated from Bloch-Siegent $B_1$-mapping; (c) original $B_0$ scale -200 to 100Hz; (d) measured $\theta$ using 2-pulse sequence with original $B_0$; $\epsilon$ adjusted $B_0$ using shim terms, scale -200 to 100Hz; (f) measured $\theta$ using 2-pulse sequence with adjusted $B_0$. Shim strengths were: $\Delta \epsilon = 500$Hz, $\epsilon = 2.2$Hz/cm, $\gamma = 0.1$Hz/cm, $x^2 = 2.0$Hz/cm², $x^2-y^2 = 0.3$Hz/cm², $xy=0.03$Hz²/cm². Results of the comparison with conventional 2-dimensional selective pulse that do not apply non-linear shims are summarized in Fig.3. Shown in columns from left to right are the effects of various pulses of 2 and 3 sub-pulses, with and without the use of non-linear shims. The simulation shows that for the excitations with 2 sub-pulses, a substantial improvement in flip angle uniformity can be achieved when using non-linear shims, whereas similar uniformity can only be achieved when one adds an additional sub-pulse (spoke) (column 3) if only linear gradients are used. When total RF duration (length of concatenated sub-pulses, excluding periods when RF is off) is kept constant, the SAR of the 2-pulse excitation employing non-linear shims is 66% higher than that of a single pulse; however, it remains below that of the spoke pulses.

Conclusions
We propose the extension of multi-dimensional excitation with non-linear $B_0$ shims to improve excitation flip angle uniformity in high field MRI. The method is demonstrated for GE MRI for human brain at 7T. The method can be combined with existing multi-dimension excitation methods, including those that use parallel excitation, and is expected to lead to improved contrast and sensitivity in GE MRI at high field.

References