Tailored Excitation Using Non-Linear B_0-Shims

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Introduction

In MRI, RF transmission field (B_1^+) 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^+. 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^+ (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 form 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.

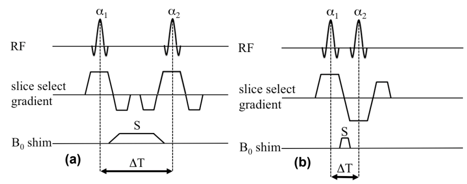

Fig. 1: Sequence diagram for shimming of B_1 exctation: (a) Basic version. (b) To minimize ΔT, the version used in this work had inverted polarity of the second slice select gradient.

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 φ corresponds to the rotation caused by the shim pulse *S*. If $\alpha_1=\alpha_2$, for any desired excitation θ, $\varphi = \arccos\left((1+\cos 2\alpha - 2\cos\theta)/1-\cos 2\alpha\right)$, which can be approximately generated by the shim currents $\varphi_{shim} = \sum_{i=1}^{n} \varphi_i = \sum_{i=1}^{n} \int \gamma c_i S_i(t) dt$ with the time integral running over the pulse interval ΔT via root-mean-squared based multi-linear regression.

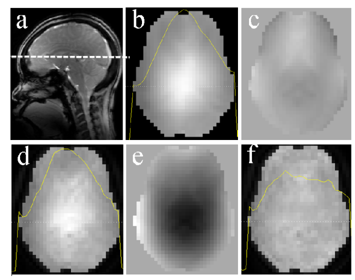

Fig. 2: Demonstration of RF flip angle shimming on human brain using 2-pulse excitation and (continuous) application of optimized shim terms

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 z^2, zx, zy, xy, x^2-y^2 field dependencies with maximum strengths of 1.6kHz/cm^2. Together with a zero order term (effectuated through either 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_i generated by the individual shim terms on a phantom. 2: Determination of subject-specific distribution of α based on B_1^+ field mapping using the Bloch-Siegert method [11] using a GE sequence and an 8 ms ±4kHz Fermi-apodized irradiation pulse. 3: Calculation of φ by substituting α into the equation above. 4: Shim optimization: It is possible to optimize the uniformity of θ over a range of sub-pulse amplitudes and choose the amplitude value that leads to the best θ uniformity or has other favorable attributes, for example minimal sensitivity to temporal variations in φ, or minimal RF power. Here, the optimization was performed by selecting a nominal sub-pulse flip angle α of 10°, which was close to the expected minimum required for the selected target angle θ, which was set at 20°, 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 φ was performed by combining the 2-pulse excitation (Fig.1b) with a GE readout using the following parameters: ΔT=1.35ms, TE=5ms, TR=600ms, 64x64 resolution FOV 27cm, slice thickness 3.5mm. The flip angle θ 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^+ profile. Simulations were performed to compare the optimized 2-pulse excitation with conventional 2- and 3-spoke pulses that did not apply higher order shims.

Results

In human brain, substantially improved θ uniformity was achieved using B_0 shimming. Fig. 2 shows an example of this for θ=20°; despite the 20% r.m.s. variation in B_1^+ over the slice, the variation in estimated θ was within 11%. The optimization was performed around φ=0, with the average α around 10°. In Fig. 2: (a) sagittal localizer indicating location of axial slice; (b) B_1^+ amplitude estimated from Bloch-Siegert B_1-mapping; (c) original B_0, scale -200 to 100Hz; (d) measured θ using 2-pulse sequence with original B_0; (e) adjusted B_0 using shim terms, scale -200 to 100Hz; (f) measured θ using 2-pulse sequence with adjusted B_0. Shim strengths were: Δf_0 = 300 Hz, x = 2.2Hz/cm, y = 9.1Hz/cm, z^2 = 2.0Hz/cm^2, x^2-y^2 = 0.3 Hz/cm^2, xy=0.03Hz/cm^2.

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.

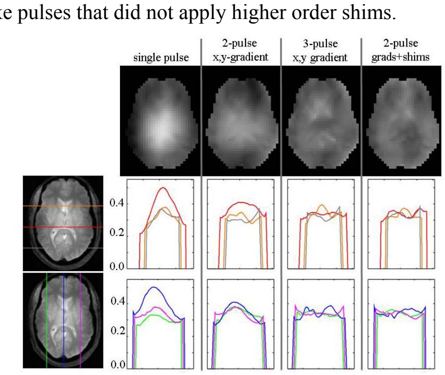

Fig. 3: Effect of the addition of non-linear shims to spatial uniformity of 2-dimensional excitation. Top row shows calculated flip angle distribution over an axial slice, plots in row 2 and 3 show profiles along lines in indicated in MRI slices shown on left.

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

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