A Novel Radiofrequency Pulse Design for Improving Flip-angle Uniformity in Ultra-high Field MRI

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Purpose

The problem of inhomogeneous B_1^+ fields in high field MRI has previously been addressed by novel or improved RF pulse designs (e.g. sparse spokes [1] and adiabatic pulses [2]) and hardware modifications (e.g. parallel transmit coils [3]). Existing techniques have practical limitations in that B_1^+ maps must be acquired for a specific imaging slice prior to the design of the RF pulse, SAR requirements hinder implementation at ultra-high field, or non-standard hardware configurations must be accommodated. The **S**equences **O**f **P**ulses **O**ptimized for a **R**ange of **I**nhomogeneities **F**or **I**maging **C**oils (SOPORIFIC) technique introduced here consists of phase and frequency modulated waveforms numerically optimized for B_1^+ immunity. SOPORIFIC pulses are effective over a specific range of frequency offsets and B_1^+ variations designated during the design process and thus can be successfully implemented regardless of field strength, transmit coil configuration, or the subject-specific spatial distribution of the B_1^+ and ΔB_0 fields.

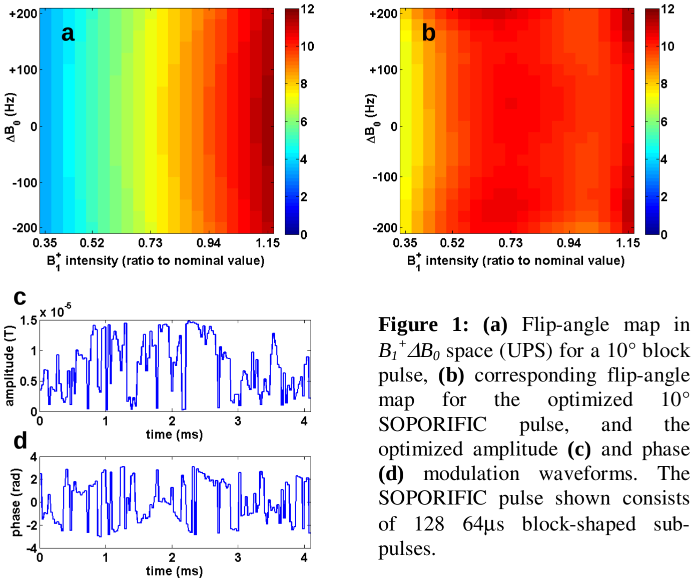

Figure 1: (a) Flip-angle map in $B_1^+\Delta B_0$ space (UPS) for a 10° block pulse, **(b)** corresponding flip-angle map for the optimized 10° SOPORIFIC pulse, and the optimized amplitude **(c)** and phase **(d)** modulation waveforms. The SOPORIFIC pulse shown consists of 128 64μs block-shaped sub-pulses.

Methods

A SOPORIFIC pulse is designed via three steps. **1)** Desired flip angles are specified for a grid (hereafter referred to as universal parameter space or UPS) of appropriate B_1^+ and ΔB_0 values. For the example presented here, respective B_1^+ and ΔB_0 ranges of 0.35-1.15 and ±200Hz were selected to represent typical variations throughout the human head at 7T while a uniform flip angle (here set to 10°) is targeted over the entire UPS. **2)** Basic amplitude and phase modulation pulse structures are determined by designating the number and duration of composite block-shaped sub-pulses as well as the maximum and minimum allowed amplitude and phase values. This step effectively fixes the number of free parameters for the numerical optimization. In this example, the pulse consists of 128 sub-pulses which are 64μs each, resulting in 256 free parameters and a total pulse duration of 4.096ms. Sub-pulse amplitudes are allowed to range from 0 to 15μT (the current Philips 7.0T hardware limit) while phase is free to vary over the entire range of ±π radians. **3)** Using custom algorithms written in C++ / Matlab (The Mathworks, Natick, MA, USA), the 128 component amplitudes and phases are optimized via minimization of the expression:

$$\sum_{i=1}^{m}\sum_{j=1}^{n}\left|\alpha_{i,j}^{S}-\alpha_{i,j}^{T}\right|$$

where i is the ith B_1^+ index in UPS, j is the jth ΔB_0 index in UPS, α^S is the flip angle according to Bloch equation simulation, and α^T is the designated target flip angle. Although a similar RF design algorithm has been previously used to produce high-bandwidth pulses for NMR spectroscopy [4], such an approach has apparently not been investigated before in the context of ultra-high field MRI.

To test its efficacy, the optimized SOPORIFIC pulse was used for non-selective excitation in a 3mm isotropic 3D GRE imaging sequence using a 17cm dielectric phantom in a Philips Achieva 7.0T human MR scanner with an eight channel T/R head coil. The resulting central-slice axial image was divided by a corresponding map of $M_0B_1^-$ as obtained from a least squares fitting of a GRE image series over a range of flip angles [1,5]. This image algebra results in a representation of the B_1^+ field associated with the SOPORIFIC pulse. As a measure of improvement, this SOPORIFIC B_1^+ map is compared to a similarly obtained B_1^+ map for a 10° block pulse.

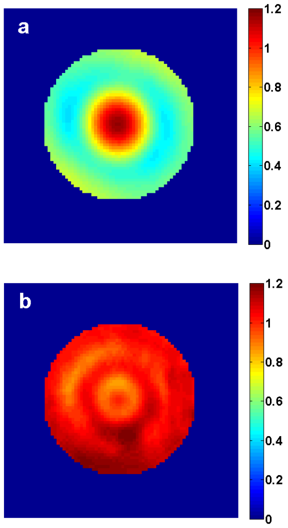

Figure 2: (a) B_1^+ map (normalized to nominal B_1^+ value) for a 10° block pulse in a 17cm dielectric phantom at 7T (mean = 0.61; range = 0.39□1.12) and **(b)** corresponding B_1^+ map for 10° SOPORIFIC pulse (mean = 1.04; range = 0.85-1.20).

Results and Conclusions

Figure 1 shows the optimized amplitude and frequency waveforms along with UPS flip-angle maps for the 10° block-shaped and SOPORIFIC pulses. Figure 2 compares 7T phantom B_1^+ maps for the 10° block-shaped and SOPORIFIC pulses. It is evident in both simulation and measurement that the SOPORIFIC pulse significantly improves flip-angle uniformity across the wide range of B_1^+ intensities encountered in ultra-high field human brain imaging. This optimized 3D excitation pulse can be readily implemented at any field strength and will improve flip-angle uniformity regardless of the geometric complexity of the subject-specific B_1^+ pattern. Thus, the pulse design technique shows much promise for practical application. Progress is currently being made with the optimization of SOPORIFIC pulses for more effective B_1^+ immunity and with similarly designed slice-selective pulses.

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References

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