A slice-selective B_1^+-insensitive composite pulse design for improved excitation uniformity at 7 T

J. Moore[1,2], M. Jankiewicz[1,3], A. W. Anderson[1,4], and J. C. Gore[1,4]

[1]Institute of Imaging Science, Vanderbilt University, Nashville, TN, United States, [2]Department of Physics and Astronomy, Vanderbilt University, Nashville, TN, United States, [3]Department of Radiology and Radiological Sciences, Vanderbilt University, Nashville, TN, United States, [4]Department of Biomedical Engineering, Vanderbilt University, Nashville, TN, United States

Purpose

The problem of inhomogeneous RF transmission (B_1^+) fields in high-field MRI has previously been addressed by various RF pulse designs (e.g. sparse spokes [1], adiabatic pulses [2,3], and composite pulses [4,5]) and hardware modifications (e.g. parallel transmit coils [6], load-insensitive coils [7], and travelling-wave antennae [8]). Existing techniques have practical limitations in that B_1^+ maps must be acquired for each specific imaging slice prior to the design of the RF pulse, SAR limits hinder implementation of some designs at ultra-high field, frequency profiles are not suited for slice selection, or non-standard hardware configurations must be accommodated. The goal of this study is to circumvent such complications by designing a novel B_1^+-insensitive, slice-selective, 90° excitation pulse suitable for use in the human brain at 7 T. The RF pulse was designed to be implementable on commercial MR scanners with a quadrature volume transmission coil. With this approach, a straightforward means of achieving uniform B_1^+ fields at high field can be provided while requiring no modifications to existing hardware and no time-consuming acquisition of subject-specific field maps.

Methods

To generate an RF pulse with the desired characteristics, amplitude and phase modulated waveforms consisting of 128 block-shaped sub-pulses, each with 32 µs duration (total pulse duration = 4.096 ms), were numerically optimized with the requirement that transverse magnetization be maximized within a specified frequency bandwidth and for a range of relative B_1^+ magnitudes characteristic of the human brain at 7 T [5]. Simultaneously, the transverse magnetization produced outside of the target bandwidth was minimized for the same range of relative B_1^+ magnitudes. Numerical optimization was carried out on a grid of frequency offsets ($\Delta\upsilon$) and $B_1^+/B_{1,nominal}^+$ values, with the $B_1^+/B_{1,nominal}^+$ range of 0.3–1.1 being divided into 17 equal parts ($\Delta B_1^+/B_{1,nominal}^+$=0.05). Inside the target frequency bandwidth of ±0.5 kHz, $\Delta\upsilon$ was divided into 41 segments ($\Delta\upsilon$ step size = 25 Hz). Outside the target bandwidth and up to ±20 kHz, $\Delta\upsilon$ was divided into 400 segments ($\Delta\upsilon$ step size = 100 Hz), with the coarser grid resolution chosen to reduce computational time. Using custom algorithms written in Matlab (The Mathworks, Natick, MA, USA), the 256 free parameters (128 amplitudes and 128 phases) were optimized via minimization of the function

$$\delta_\perp(\vec{A},\vec{\phi}) \;=\; \lambda\left(\frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n}\left|M_{i,j}^{\perp}(\vec{A},\vec{\phi})-1\right|\right) \;+\; (1-\lambda)\left(\frac{1}{pq}\sum_{u=1}^{p}\sum_{v=1}^{q}\left|M_{u,v}^{\perp}(\vec{A},\vec{\phi})\right|\right)$$

where i and j (u and v) are the optimization grid indices inside (outside) the target bandwidth, $M^\perp$ is the transverse magnetization, and λ is a constant (0.5 for the pulse in Fig. 1) determining the relative weighting of the two grid regions. Sub-pulse amplitudes were constrained to a range of 0–15 µT while phases were free to vary over the entire range of ±π radians.

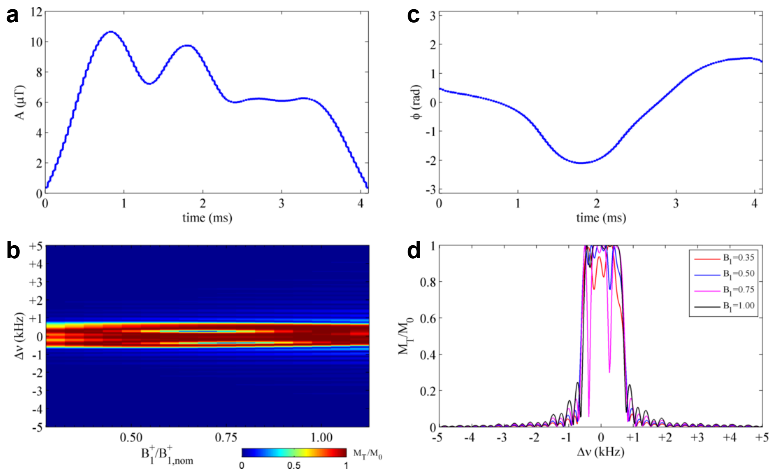

Fig. 1 (a) optimized amplitude modulation waveform consisting of 128 block-shaped sub-pulses, each with 32 µs duration; **(b)** optimized phase modulation waveform; **(c)** simulated values of transverse magnetization for the optimized pulse over a range of relative B_1^+ magnitudes (horizontal axis) and frequency offsets (vertical axis); **(d)** simulated frequency profiles for various relative B_1^+ magnitudes.

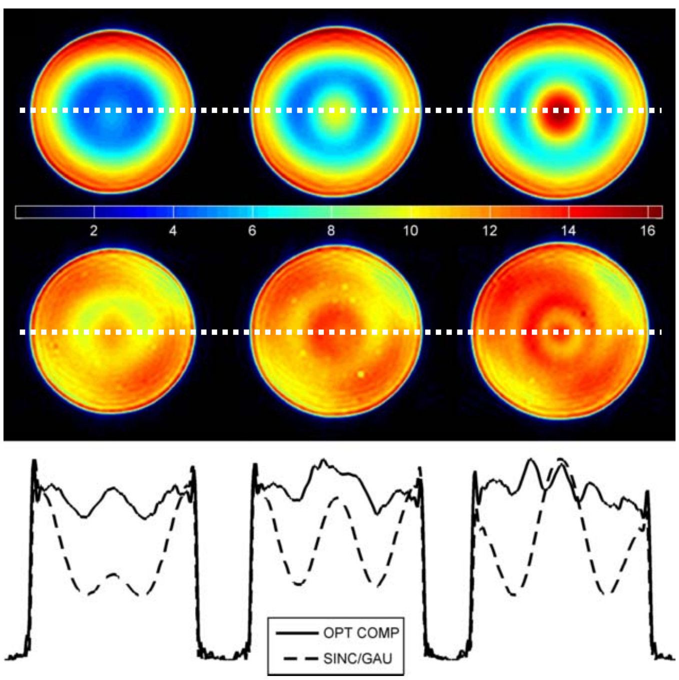

Fig. 2 (1st row) 3 slices of a 7 T multi-slice gradient echo imaging experiment using a 90° gaussian-modulated sinc pulse for slice-selective excitation in a 17 cm dielectric phantom; **(2nd row)** corresponding images obtained with the optimized composite pulse used for excitation; **(3rd row)** line profiles corresponding to horizontal white dotted lines. Colors indicate image intensity in arbitrary units. Line profiles are normalized to the maximum intensity of the given image. The composite pulse clearly results in much improved image uniformity despite the large variations of RF intensity present at 7 T.

Results and Conclusions

Optimization resulted in a highly B_1^+-insensitive, 90° excitation pulse with smoothly varying amplitude and phase modulation waveforms, a 1.26 kHz bandwidth (FWHM), and a sharp frequency profile (Fig. 1). Multi-slice gradient echo images of a phantom in a 7 T Philips MR scanner with a volume T/R head coil reflect the vastly improved flip-angle uniformity achieved by the optimized pulse as compared to a Gaussian-modulated sinc pulse (Fig. 2). The optimized slice-selective 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. The pulse design technique thus provides a straightforward and cost-effective tool for improving flip-angle uniformity at high field.

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References

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