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

J. E. Moore1, M. Jankiewicz1,2, H. Zeng1,2, A. W. Anderson1,3, M. J. Avison1,3, E. B. Welch1,4, and J. C. Gore1,3

1Institute of Imaging Science, Vanderbilt University, Nashville, TN, United States, 2Department of Radiology, Vanderbilt University, 3Department of Biomedical Engineering, Vanderbilt University, 4Philips Healthcare, Cleveland, OH, United States

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 Sequences Of Pulses Optimized for a Range of Inhomogeneities For Imaging Coils (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 $\Delta B_0$ fields.

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 $\Delta B_0$ values. For the example presented here, respective $B_1^+$ and $\Delta B_0$ 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:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} |\alpha_i^j - \alpha_i^{j*}|$$

where $i$ is the $i$th $B_1^+$ index in UPS, $j$ is the $j$th $\Delta B_0$ index in UPS, $\alpha^i$ is the flip angle according to Bloch equation simulation, and $\alpha^{j*}$ 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 $M_0 B_1^+$ 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.

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.

Acknowledgments: This work was supported by NIH grant number RO1EB000461.

References