An Optimized Composite Refocusing Pulse for Ultra-High Field MRI

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Purpose
At high magnetic fields, the wavelengths of the RF pulses transmitted in MRI are comparable to the size of the human torso/head [1], which gives rise to inhomogeneous B_1^+ fields. Variations of the RF field can be reduced (for example) by the use of tailored slice-selective pulses optimized for the desired excitation profile [2] based on spokes or an optimized composite pulse with slice selection [3]. A refocusing pulse is often needed in various imaging scenarios. Solutions currently used in use involve adiabatic refocusing pulses, or sequences of sinc-pulses susceptible to field inhomogeneities. A design of a composite refocusing pulse suitable for use in human imaging at 7T is presented here. With the assumption that it is preceded by a slice-selective excitation, the refocusing solution is immune to inhomogeneities within a predefined universal parameter space of B_1^+ and ΔB_0 values (UPS).

Methods
In our preliminary work, we used a composite, amplitude- and phase-modulated, pulse consisting of a train of 40 block sub-pulses, which are each 192µs long. The amplitude and phase of each sub-pulse was subject to numerical optimization, leading to 80 free parameters and a total pulse duration of 7.68ms. Sub-pulse amplitudes are allowed to range from 0 to 15µT while phase is free to vary over the entire range of ±π radians.
A set of custom Matlab (The Mathworks, Natick, MA, USA) optimization routines were written to handle the minimization of the expression:

$$\sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left|M_x^{init}(i,j)+M_x^{final}(i,j)\right|+\left|M_y^{init}(i,j)-M_y^{final}(i,j)\right|\right]_{BW}$$

where i is the ith B_1^+ index in the UPS, j is the jth ΔB_0 index in UPS, UPS grid size was fixed to m=17 and n=41 (21 inside and 40 outside of the slice profile) for the purpose of numerical optimization. M_x^{init} , M_y^{init} correspond to the initial value of the transverse components of magnetization after execution of the

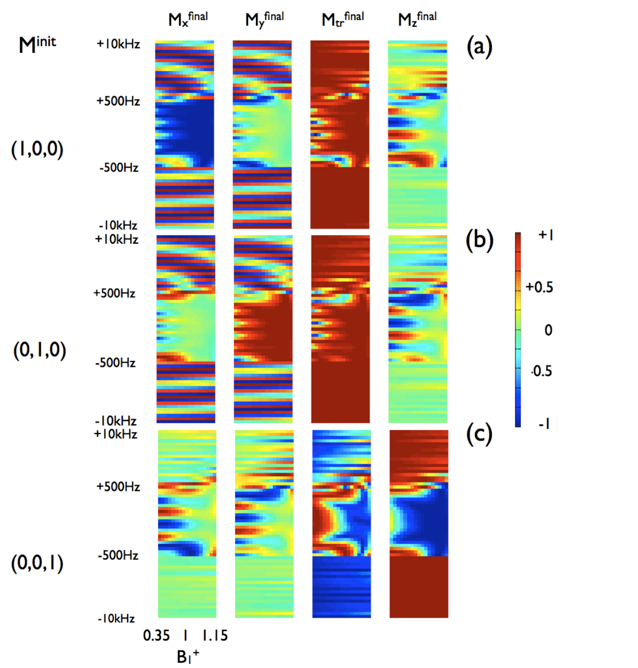

Fig.1: All three components of the magnetization vector, together with a transverse magnetization, after execution of the optimized composite refocusing pulse. The values of the magnetization are given on a UPS grid of values from 0.35-1.15 in B_1^+ and +-10kHz ΔB_0 directions. The pulse is optimized for 1kHz bandwidth. The pulse performance is represented for three mutually orthogonal initial conditions (1,0,0) (a), (0,1,0) (b) and (0,0,1) (c). A slice profile is visible on M_z^{final} (c).

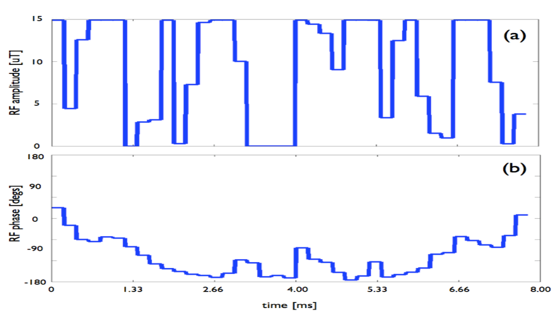

Fig.2: Waveforms of the optimized refocusing pulse, consisting of 40 192µs block-shaped sub-pulses with optimized amplitude (a) and phase (b).

slice-selective excitation pulse executed immediately before the refocusing pulse. The optimization was performed on an orthogonal basis of magnetization (M_x^{init} , M_y^{init} , M_z^{init}) vectors (1,0,0) and (0,1,0) and (0,0,1), where the third component corresponds to longitudinal final magnetization (not included in the optimization). M_x^{final} and M_y^{final} are the magnetization components found through numerical solution of Bloch equations in the presence of B_1^+ inhomogeneity and ΔB_0 frequency offset for the purpose of slice-selection and after execution of the refocusing pulse under consideration. The subscript BW (bandwidth) is here to remind us that we are dealing with a slice-selective pulse and hence the values of the initial magnetization matrices are weighted with -1 and +1 outside and inside of the slice profile. In the example presented here, B_1^+ range [3] of 0.35-1.15 (in 0.5 increments) as measured in units of nominal B_1^+ were selected to represent typical variations throughout the human head at 7T. On the optimization grid, the ΔB_0 range corresponding to the 1kHz target bandwidth was divided into 47.6Hz increments and the +/-10 kHz region outside the target bandwidth was more coarsely divided into 500 Hz increments in order to reduce computational time while still forcing the desired slice-selection properties (selected here to represent a typical slice thickness and gradient strength).

Results and Conclusions
Figure 1 shows all three components of the final magnetization vector as well as transverse magnetization, directly after the refocusing pulse for three mutually orthogonal initial magnetization values (1,0,0) (a), (0,1,0) (b) and (0,0,1) (c). A slice profile can be seen in Fig. 1(c) due to the nature of the corresponding initial condition. The magnetization in the M_x-direction changed direction from +1 to -1 whereas magnetization in the M_y-direction conserved its initial value. The longitudinal component of the magnetization M_z changed direction to the opposite, ensuring a 180° rotation of the magnetization vector along the M_y-axis. Figure 2 shows the designed refocusing pulse generating the desired magnetization behavior. The optimized refocusing pulse presented here can be implemented at any field strength. The solution presented here is independent of subject specific factors or the precise geometric complexity of B_1^+ patterns, and so it represents a robust alternative to existing refocusing scenarios. Future work involves further perfection of the slice-selection profile behavior for spectroscopy as well better optimization within a given $B_1^+/\Delta B_0$ range.

Acknowledgments: This work was supported by NIH grant number RO1EB000461. **References:** **[1]** P. Van de Moortele et al.: B_1 Destructive Interferences and Spatial Phase Patterns at 7T with a Head Transceiver Array Coil, Mag Reson Med 54: 1503 (2005); **[2]** K. Setsompop et al.: Sparse Spokes Slice Selective Design for B_1 inhomomogeniety corrections at 7T, Proc Intl Soc Mag Reson Med 15: 256 (2007). **[3]** J. Moore, M. Jankiewicz, et *al*., *Proc. ISMRM 4866, Honolulu, HI, USA* (2009).