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Slice-selective excitation with B_1^+-insensitive composite pulses

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ABSTRACT

Spatially selective excitation pulses have been designed to produce uniform flip angles in the presence of the RF and static field inhomogeneities typically encountered in MRI studies of the human brain at 7 T. Pulse designs are based upon non-selective, composite pulses numerically optimized for the desired performance over prescribed ranges of field inhomogeneities. The non-selective pulses are subsequently transformed into spatially selective pulses with the same field-insensitive properties through modification of the spectral composition of the individual sub-pulses which are then executed in conjunction with an oscillating gradient waveform. An in-depth analysis of the performance of these RF pulses is presented in terms of total pulse durations, slice profiles, linearity of in-slice magnetization phase, sensitivity to RF and static field variations, and signal loss due to T_2^* effects. Both simulations and measurements in phantoms and in the human brain are used to evaluate pulses with nominal flip angles of 45° and 90°. Target slice thickness in all cases is 2 mm. Results indicate that the described class of field-insensitive RF pulses is capable of improving flip-angle uniformity in 7 T human brain imaging. There appears to be a subset of pulses with durations $\lesssim$10 ms for which non-linearities in the magnetization phase are minimal and signal loss due to T_2^* decay is not prohibitive. Such pulses represent practical solutions for achieving uniform flip angles in the presence of the large field inhomogeneities common to high-field human imaging and help to better establish the performance limits of high-field imaging systems with single-channel transmission.

1. Introduction

The problem of spatially-dependent signal variations arising from non-uniformities in the strength of the transmitted radio frequency field (B_1^+) [1] has received much attention over the last decade due to the proliferation of high-field ($\geqslant$3 T) magnets for human MR imaging and spectroscopy. The challenge of mitigating such signal variations in order to better realize the potential of high-field imaging systems has sparked a renewed interest in the design of RF pulses that invoke a magnetization response insensitive to the B_1^+ field strength [2–11]. Due to non-selective frequency profiles and non-linear transverse magnetization phase in the through-slice direction, many such pulses are limited in application to whole-volume acquisitions. Related pulse designs that could provide the B_1^+-insensitivity needed for high-field applications while additionally permitting slice-selective imaging by way of a gradient-recalled echo (GRE) are therefore of interest. Design criteria for such a class of pulses are extensive and include: (1) durations short enough to avoid significant T_2^* signal loss at 7 T; (2) bandwidths suitable for imaging thin ($\lesssim$5 mm) slices without slice profile distortions due to in-plane B_0 variations; (3) linear (or quasi-linear) through-slice magnetization phase profiles that allow for rephasing using linear gradients (i.e., GRE); (4) slice profiles suitable for highly selective imaging (i.e., profiles comparable to those attained with Gaussian or apodized sinc pulses); (5) peak amplitudes consistent with the performance limits of typical RF amplifiers used by clinical scanner manufacturers; and (6) average RF power levels that permit safe scanning of human subjects given the currently accepted limits on specific absorption rates (SAR $\lesssim$ 3 W/kg in the brain [12]).

Although the above requirements for B_1^+-insensitive slice selection are daunting, progress has been made recently in the development of such pulses. In 1993, a gradient modulation technique was demonstrated as a means for achieving spatial selectivity for composite excitation pulses [13]. The technique relied upon a series of gradient lobes of alternating polarity—each of which was responsible for allowing the spatial selectivity of a given sub-pulse in the composite waveform while simultaneously rephasing the magnetization produced by the prior sub-pulse. Today, this approach is widely adopted in the design of *sparse spokes* pulses used for flip-angle inhomogeneity corrections [14,15] but has proven adaptable to other pulse types. In 2008, Balchandani et al. [8] used

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such oscillating selection gradients to transform a non-selective BIR-4 excitation pulse into a spatially selective pulse with similar B_1^+-insensitive properties. In this technique, BIR-4 phase and amplitude modulation patterns served as envelopes defining the phases and amplitudes of a train of spectrally selective sub-pulses formed from the central lobes of `sinc` functions (hereafter referred to as a SINC modulation). In the context of a GRE sequence with a 90° excitation, the study showed improvements in flip-angle uniformity for 10 mm slice thicknesses in a phantom and the *in vivo* human brain at 3 T and represents a significant step in advancing the limits of practical single-channel pulse designs.

The work presented here uses the same spatial selectivity strategy as that discussed above but in conjunction with composite pulses designed to produce uniform flip angles over specified ranges of B_0 and B_1^+ field strengths [10] and is thus akin to recent work by Matson et al. [16] and Boulant et al. [17]. In general, this class of composite pulses is characterized by non-selective composite pulses numerically optimized for insensitivity to field variations and subsequently endowed with spectral selectivity via the use of shaped sub-pulses, e.g., Gaussian (hereafter referred to as GAU) or SINC sub-pulses. Furthermore, optimization cost functions do not rely explicitly on fulfillment of the adiabatic condition to achieve immunity to B_1^+ variations. This latter characteristic is potentially advantageous given that the pulse durations and high RF power needed for adiabaticity are not always attainable in the human brain at 7 T due to the combination of large B_1^+ variations, RF amplifiers with limited peak amplitudes, SAR restrictions, and relatively short T_2^* values. In addition to corroborating the findings of existing works (i.e., [8,16,17]), the present study uniquely contributes to the knowledge of such pulse designs through investigating (1) the efficacy of an alternative optimization protocol, (2) the use of higher gradient strengths for achieving imaging slice thicknesses of ~2 mm, (3) the slice profile variations resulting from different sub-pulse amplitude modulations (i.e., GAU and SINC), (4) the use of a wide range of total pulse durations (~2–20 ms) so as to explore the potential trade-off between pulse performance (i.e., insensitivity to B_1^+ and B_0 variations) and relaxation effects (i.e., T_2^* and $T_{2,\rho}$ [18,19]), and (5) the application of such pulses to multiple subjects without using subject specific optimizations.

Given these specific objectives, the underlying motive of the present study was to further test the limitations of single-channel, slice-selective pulse designs for practical use at 7 T. While multi-transmit technologies promise to meet many of the same needs, single-channel pulse designs are very much of interest given that all scanners are not yet equipped with multi-transmit hardware and that the SAR demands of multi-transmit systems have not been fully established. Furthermore, the pulses of this study have an inherent advantage over current multi-transmit methods in that subject-specific field maps and subsequent pulse calibrations do not have to be made—pulses are designed with the goal of delivering the required performance despite widespread differences in B_0 and B_1^+ field geometries.

2. Methods

The description of methods is presented in three main parts: pulse designs, simulations, and experiments.

2.1. Pulse designs

2.1.1. Structure and optimization of non-selective pulses

The first step of the pulse design process was to generate non-selective composite pulses with inherent insensitivity to variations in the B_0 and B_1^+ fields. This was accomplished with a pre-existing protocol [10] for numerical optimization that employs a discrete grid of relevant ΔB_0 and B_1^+ values. The ΔB_0 and B_1^+ ranges of this grid were chosen to be ±150 Hz and [0.25, 1.00], respectively, with the latter being in units of the nominal B_1^+ field strength $\left(B_{1,\mathrm{nom}}^+\right)$. These choices designate the field variations over which the resulting pulse is required to perform and were guided by the previous 7 T study [10]. Field ranges were discretized into 31 steps in the ΔB_0 direction (resulting in steps of 10 Hz) and 16 steps in the B_1^+ direction (resulting in steps equivalent to 5% increments of $B_{1,\mathrm{nom}}^+$). The resulting B_1^+-ΔB_0 grid provided a visualization tool when magnetization response to a given RF pulse was simulated and also served as a basis for formulating the numerical optimization problem.

Just like those from our previous work [10], the non-selective pulses of the present study consist of sub-pulses with constant phase and amplitude; however, the new pulses differ from the previous ones in that (1) sub-pulse duration was significantly lengthened to accommodate the substitution of GAU and SINC modulations needed for slice selection and (2) peak RF amplitudes were further limited such that necessary amplitude adjustments for the slice-selective sub-pulses could be made without exceeding the peak RF limit of 15 μT. These constraints resulted in sub-pulse durations of 665.6 μs and 1062.4 μs (integer multiples of the digital RF amplifier's dwell time of 6.4 μs) and maximum amplitudes of 8.8 μT and 5.0 μT for the SINC and GAU formats, respectively. Motivation for these particular duration and amplitude values is further described in Section 2.1.2.

With sub-pulse durations and maximum amplitude values fixed, the k phases ($\phi = \{\phi_1, \phi_2, \ldots, \phi_k\}$) and k amplitudes ($\mathbf{A} = \{A_1, A_2, \ldots, A_k\}$) of a given sequence of block-shaped sub-pulses were determined through minimization of the cost function

$$\delta_\alpha(\mathbf{A}, \phi) = \frac{1}{m \cdot n} \sum_{i,j=1}^{m,n} \left| \frac{\alpha_{i,j}^S(\mathbf{A}, \phi) - \alpha_{i,j}^T}{\alpha_{i,j}^T} \right|, \tag{1}$$

where i is the B_1^+ index (with $m = 16$) on the B_1^+-ΔB_0 grid, j is the ΔB_0 index (with $n = 31$) on the B_1^+-ΔB_0 grid, and α is the flip angle given by $\cos^{-1}(M_z/M_0)$ with S and T denoting simulated and target values. In this study, $\alpha_{i,j}^T$ values were set to either 45° or 90° over the entire optimization grid, thus prescribing uniform flip angles over the specified ranges of field variations. The value of δ_α represents the average deviation of simulated flip angles from the target flip angle over the entire B_1^+-ΔB_0 grid and is expressed as a fraction of the target flip angle. Solutions to the minimization problem were found using the `fmincon` function in Matlab (The MathWorks, Natick, MA, USA) with the `interior-point` algorithm. This constrained minimization technique involves numerical approximations to the Hessian of the LaGrangian of δ_α in combination with a series of linear and conjugate-gradient steps. Initial conditions for all optimizations were defined by randomly assigned phase and amplitude values for each sub-pulse (within the constraints of $-\pi \leqslant \phi_k \leqslant +\pi$ and $0 \leqslant A_k \leqslant 15\ \mu\mathrm{T}$) and an initial magnetization vector of $\mathbf{M}_0 = (M_x, M_y, M_z) = (0, 0, 1)$. The numerical optimization was carried out for four categories of pulses corresponding to the two target flip angles (45° and 90°) and the two amplitude/duration formats (GAU and SINC) described above. Within each category, composite pulses were generated with k = 1, 2, ..., 19 sub-pulses, thus reflecting the desired range of total pulse durations to be investigated, i.e., $\Delta T \sim$ 1–20 ms (see Section 2.1).

Despite the relatively low number of free parameters in the optimization problem (e.g., the maximum number is 40 in the case of 20 sub-pulses), the minimization algorithm was found to be rather sensitive to initial conditions. To ensure avoidance of outlying local minima, the optimization was repeated 100 times for each pulse as defined by a unique combination of target flip angle (α^T), total duration (ΔT), sub-pulse duration, and maximum sub-pulse amplitude values. Only phase and amplitude sets resulting in the lowest value of δ_α for a given pulse structure were considered in