New Slice-Selective Pulse Cascades Producing Uniform Tipping in Inhomogeneous RF Fields

G. B. Matson[1,2], L. G. Kaiser[1,3], and K. Young[1,2]

[1]CIND, Veterans Affairs Medical Center, San Francisco, CA, United States, [2]University of California, San Francisco, CA, United States, [3]Northern California Institute for Research and Education, San Francisco, CA, United States

Introduction: Although MRI at high field (4.0 Tesla and higher) yields improved signal-to-noise, it also comes with increased challenges. Chief among these is the inherently non-uniform RF (B_1), which causes spatially dependent tipping of magnetization and results in both spatially dependent intensity distributions and spatially dependent contrast. While the spatially dependent intensity is potentially correctable, there is no correction for the spatially dependent contrast. There have been two main approaches to address the problem of non-uniform tipping at high field. The first approach makes use of simultaneous excitations of multiple coils (or coil ports) to generate a more uniform B_1 field (1). The second approach uses multidimensional pulses to produce uniform tipping in the presence of non-uniform B_1 fields. While the length of conventional multidimensional pulses causes difficulties, the length can be alleviated by transmit SENSE methods (2). However, transmit SENSE also requires the use of multiple transmit channels for simultaneous excitation of multiple coils. Thus, both of these approaches are technically challenging and potentially quite expensive. In contrast, we recently introduced pulse cascades that can provide uniform tipping over modest ranges of B_1 inhomogeneity and spin resonance offset (3). The cascade design used optimization of a rectangular pulse cascade for immunity to both B_1 inhomogeneity and resonance offset, followed by conversion to a cascade of slice-selective pulses (3). These cascades can be implemented on a conventional MRI instrument without the need for specialized hardware. The chief drawback of these cascades is that they generate much higher SAR than the pulse they replace. Thus, our goal was to design pulse cascades of lower SAR, without sacrificing uniform tipping over a range of B_1 inhomogeneity and resonance offset.

Methods: We hypothesized that the use of off-resonance as a design parameter could provide additional flexibility for design of pulse cascades with immunity to both B_1 inhomogeneity and to spin resonance offset. Furthermore, we believe our use of off-resonance constitutes a new design method not previously used for cascade or composite pulse design. An additional attraction for this design was that the off-resonance component of the tipping field would not contribute to SAR. Accordingly, the Mathematica program described in (3) for optimization of rectangular pulse cascades was modified to incorporate off-resonance into the optimization.

Results: Our optimization results incorporating off-resonance produced lowered SAR rectangular pulse cascades with improved immunity to B_1 inhomogeneity and to resonance offset. However, the frequency-selective pulse shapes generated with MATPULSE (4) and used to convert from rectangular to slice-selective pulses produced markedly distorted profiles when used with the off-resonance pulses. To overcome this problem, each off-resonance pulse was converted into two identical frequency-selective shapes, applied with gradients of opposite signs. This approach produced acceptable slice-selective profiles provided the off-resonance pulses were limited in both rotation angle and degree of off-resonance. Figure 1 shows the transverse magnetization for a three pulse rectangular sequence producing a 90^0 tip as a function of B_1 strength (arbitrary units, with 100 being the nominal B_1 strength). A graph tracing the isochromats experiencing differing B_1 field strengths over the unit sphere (trace diagram) is shown in Fig. 2, where the middle pulse is an off-resonance pulse, and the direction of the B_1 field for the final tip is shown in red. Figure 3 shows the RF waveforms following conversion to a slice-selective cascade, where the middle 120^0 off-resonance pulse has been converted into two 60^0 off-resonance pulses, and the waveforms of the cascade are applied in the presence of gradients of alternating sign (3). Figure 4 shows magnitude profiles of the slice selective cascade over a B_1 range of +/- 25%. This cascade provided similar performance to the previously developed four pulse slice-selective cascade using nominal slice-selective pulses of 90^0 (3); however, the off-resonance cascade used nominal slice-selective pulses of 45^0, 60^0, 60^0 and 72^0, to generate only half of the SAR produced by the on-resonance design.

Summary: We have used off-resonance as a design parameter to generate new rectangular pulse cascades composed of both on-resonance and off-resonance pulses that generate uniform tips in the presence of inhomogeneous B_1 fields and spin resonance offsets. In this preliminary investigation the conversion into slice-selective versions required limiting both the rotation angle and degree of off-resonance of the pulses. Nevertheless, as demonstrated here, cascades of similar performance to on-resonance cascades could be produced, but with lowered SAR. Incorporation of improved pulse shapes for the off-resonance pulses could extend the performance of these designs to provide cascades of still lower SAR, or improved performance as compared to on-resonance designs.

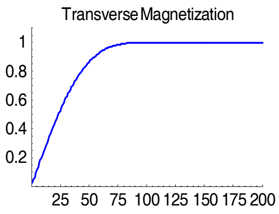

Fig. 1. Mxy *vs* B_1 strength.

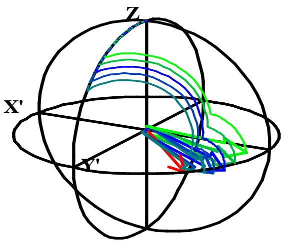

Fig. 2. Trace diagram.

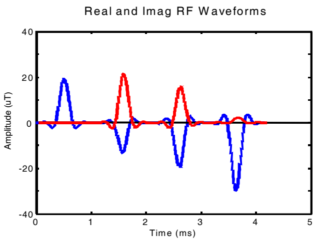

Fig. 3. RF Waveform.

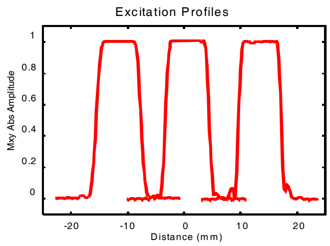

Fig. 4. Magnitude profiles at nominal and +/- 25% B_1 strengths.

References:

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