Broadband, Shallow Tip NMR Pulse Design Providing Uniform Tipping in Inhomogeneous RF Fields

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Introduction

Although high-field MRI on the human head offers a number of advantages including increased signal-to-noise ratio (SNR), and higher contrast for certain applications, there are also significant difficulties. Chief among these are the non-uniform tipping (variation of the flip angle in the sample) produced by conventional RF pulses due to the inhomogeneous RF (B_1) field intrinsic in tissues at high field, and the increased Specific Absorption Rate (SAR) produced by RF pulses at high field. The non-uniform tipping leads to spatially dependent contrast and sub-optimal SNR, thus complicating the interpretation of MR images. Conventional approaches to overcome the non-uniform tipping include 1) B_1 shimming, which involves adjustment of multiple RF inputs into coil structures with multiple RF channels to achieve a more uniform B_1 field, and 2) multidimensional RF pulses designed to produce uniform tipping over a particular slice, again applied with multiple RF inputs simultaneously to multiple coil channels to achieve pulses of reasonable duration. An additional suggestion has been the use of more complicated coil structures that achieve a more uniform B_1 field over the human head [1]. Recently, a new approach has been suggested making use of broadband (non-slice selective) pulses which produce uniform tipping even in the presence of non-uniform B_1 fields [2,3]. Such pulses could potentially be used for 3D imaging experiments such as 3D MPRAGE, which typically uses non-slice selective pulses. Advantages of this approach include the fact that prior B_1 field measurements are not required, and the pulses can be used with conventional head coils. However, these previously designed pulses for uniform tipping were much longer than the rectangular pulses they replaced, and also generated considerable SAR. Thus, the aim of this study is to introduce a new, more efficient RF pulse design for shallow tip broadband pulses (non-slice selective) by using an optimal control strategy [4] to achieve uniform tipping in the presence of inhomogeneous B_1 fields.

Materials and Methods

We previously developed a composite pulse design for generation of shallow tips using an optimization package in Mathematica (Wolfram Research, Inc. USA). The composite pulse consisted of a cascade of four 90 degree (nominal tip) pulses which produced a shallow tip pulse with immunity to B_1 inhomogeneity and to resonance offset. The weakness of this composite pulse was its inefficiency; a total rotation of 360 degrees was required to achieve a net tip of 10 or 20 degrees. In addition, it produced too much SAR to be practical. To obtain a more efficient pulse, we developed an optimization routine based on optimal control theory [4] and incorporated it into MatPulse [5,6]. The composite pulse was then submitted to our optimal control routine. Inputs for the optimization included the desired tip angle, maximum B_1 strength, and additional parameters for the optimization including the desired range of immunity to B_1 inhomogeneity and to resonance offset. The MatPulse [6] program is written in Matlab (The MathWorks, Inc. USA) and is available from the CIND website (http://www.cind.research.va.gov/).

Results

Design Example for 4.0 T: Figure 1 shows a 10 degree pulse in terms of real and imaginary components with a B_1 maximum (B_1max) of 7 uT and a length of 1.4 ms. The performance of the pulse is shown in the contour plot of fig. 2, which indicates that the pulse performs well (just a few percent variation in tip angle) over a B_1 range of +/- 20%, and over a resonance offset range of over +/- 100 Hz. While greater immunity may be requested in the design process, the pulse must be lengthened (or the B_1max limit raised) to maintain the same level of performance. The pulse is scalable, so that the B_1max can be reduced at the expense of lengthening the pulse and diminishing the immunity to resonance offset. Finally, the basic design can be used for tips of under 10 degrees to over 40 degrees, although some lengthening of the pulse is required to maintain the same level of performance as the tip angle is increased.

Comparison to Other Pulses: Boulant et al. [2] showed what they termed a strongly modulated pulse (SMP) for 7.0 T applications with a B_1max of 7 uT and a length of 3.3 ms. This pulse produces a 30 degree tip in the presence of B_1 inhomogeneity of roughly a factor of 2, and over a range of resonance offsets of +/- 100 Hz. Although this SMP pulse does reduce the variation in tip angle over that of a conventional pulse, there is still considerable variation in tip angle. For comparison, figs. 3 and 4 show our design of a 2 ms, 30 degree pulse with a B_1max of 7 uT. Figure 4 indicates a performance similar to the SMP pulse, but at a shorter duration (just over 2 ms compared to 3.3 ms). Moore et al. [3] demonstrated a 10 degree SOPORIFIC pulse with a B_1max of 15 uT that appears to perform well, but has a length of 4 ms, while a pulse with similar performance with our design (not shown) is approximately 1 ms. Thus our design appears to provide more efficient pulses with less SAR than either the SMP or SOPORIFIC design methods.

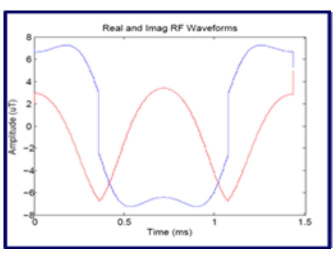

Fig.1. 10° pulse.

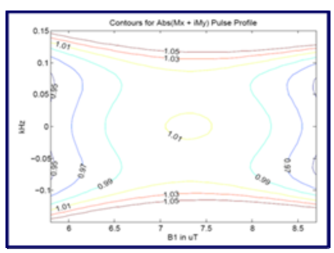

Fig. 2. Contour plot of the10°pulse performance.

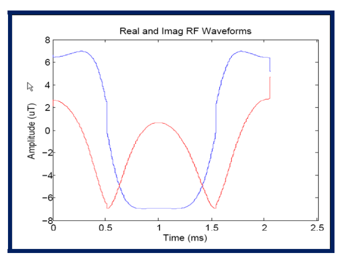

Fig. 3. 30° pulse.

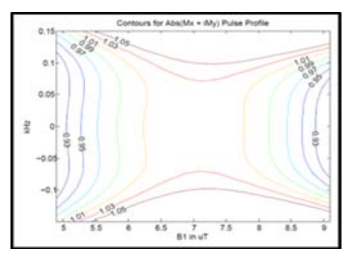

Fig. 4. Contour plot of the 30° pulse performance

Conclusion

This study shows a new pulse design for broadband, shallow tip pulses which potentially have promise for high field MRI applications. The design can provide pulses with specified immunities to B_1 inhomogeneity and to resonance offset, and can be used for tips ranging from under 10 degrees to over 40 degrees. However, as these pulses are still invariably much longer than the rectangular pulses they replace, they have the disadvantages of producing increased SAR and also generating undesirable magnetization transfer (MT) effects. Thus, MRI sequences will have to be re-designed to utilize these new pulses. In particular, the number of pulses/sec used for 3D MP RAGE must be reduced, and a greater amount of k-space data collected following each pulse in order to accommodate the high SAR and to mitigate the MT effects of individual pulses without lengthening the duration of the MRI experiment. This work is supported by NIH grants 5R01EB000766 and 1P41RR023953.

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