RF Pulses for In Vivo Spectroscopy at High Field Designed Using Optimal Control

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INTRODUCTION

Localized *in vivo* spectroscopy at high magnetic field strength (> 3 T) is susceptible to localization artifacts such as the chemical shift artifact and the spatial interference for J-coupled spins (1-2). This latter artifact results in regions of anomalous phase for J-coupled spins. Approaches to minimize these artifacts include increasing the bandwidth of the localization pulses, and use of frequency selective saturation pulses to suppress the signals with anomalous phase (3). Although optimal control methods were initially used for design of frequency selective RF pulses (4-5), the much more efficient Shinnar Le-Roux (SLR) method became the RF pulse design method of choice (6). Recently, there has been a resurgence in the use of optimal control methods for the design of RF pulses for high resolution NMR, promoted primarily by the research groups of Glaser and Skinner (G&S) (7-9). The goal here is to demonstrate the efficacy of optimal control methods to provide broader bandwidth localization pulses for *in vivo* spectroscopy in the presence of limited RF power. It is shown by examples that the use of optimal control enables the generation of i) improved bandwidth excitation pulses, ii) more efficient selective inversion pulses to be used for generation of spin echoes, and iii) improved frequency selective saturation pulses.

METHODS

To facilitate the design and examination of the new pulses, optimal control routines similar to those reported on by the G&S groups (7), but extended to include frequency selectivity, were incorporated into MatPulse (10). The MatPulse implementation provided options for broadband non-selective pulses and frequency selective pulses. For frequency selective pulses, selection of the passband and stopbands, along with the number of points in the bands, was enabled. Additional extensions included selection of single-sided or symmetrical pulse rejection bands, and Gaussian weighting of the passband and stopband regions. Although the MatPulse implementation included the ability to specify the desired degree of immunity to B_1 inhomogeneity, that feature was not used for the new pulses presented here. However, the program was tested for its ability to generate broadband pulses previously designed by the G&S groups (8), and also to generate spin echo pulses similar to those of Schulte et al. (11), and saturation pulses similar to those of Schulte et al. (12) (Results not shown). The MatPulse program is available at the CIND website (http://www.cind.research.va.gov/).

RESULTS

Our experience with the Schulte et al. (11) spin echo pulses indicated that, in cases where the maximum B_1 was limiting, it was more efficient to use dual inversion pulses than a single spin echo pulse. Thus, for spin echo pulses we concentrated on inversion pulse designs, where dual inversion pulses could be used to generate a spin echo. All pulses were designed for a bandwidth of 8 kHz, and to not exceed a B_1 maximum of 30 uT (approximately 1278 Hz). i) For the excitation pulse, the initial pulse submitted to the optimal control routine was an 8 kHz bandwidth pulse with a B_1 maximum of approximately 60 uT. The resulting pulse (real and imaginary waveforms) is shown in Fig. 1A, and the refocused profile in Fig. 1B. ii) For the inversion pulse, we used an initial hyperbolic secant pulse to obtain the inversion pulse (real and imaginary waveforms) shown in Fig. 2A, with the profile shown in blue in Fig. 2B. The profile in red is for a HS2 pulse (13) that was 50% longer than the optimal control designed pulse in order to achieve a similar profile. iii) For the saturation pulse, we specified a single-sided saturation pulse (as only a single side was needed for the purpose for which the pulse was designed), with the result (real and imaginary waveforms) shown in Fig. 3A, and the profile in Fig. 3B. All of the pulse profiles were generated with the MatPulse Bloch equations.

SUMMARY

The optimal control routine enabled the excitation pulse bandwidth to be extended over that of an SLR pulse by approximately a factor of 2, and enabled the inversion pulse to be significantly shortened over our best efforts with a HS2-style pulse. The optimal control routine also enabled a more efficient saturation pulse to be designed by virtue of optimizing just a single side. These optimal control designed pulses represent new designs that should prove beneficial for high field *in vivo* spectroscopy.

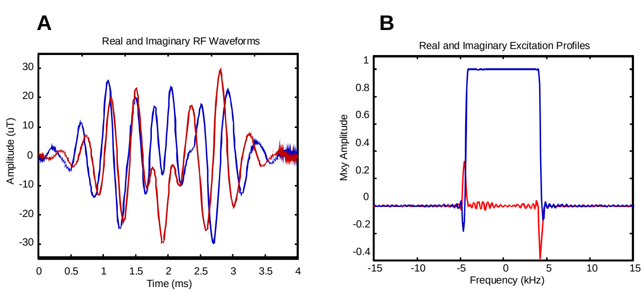

Fig. 1. A Excitation pulse. B Resulting refocused profile.

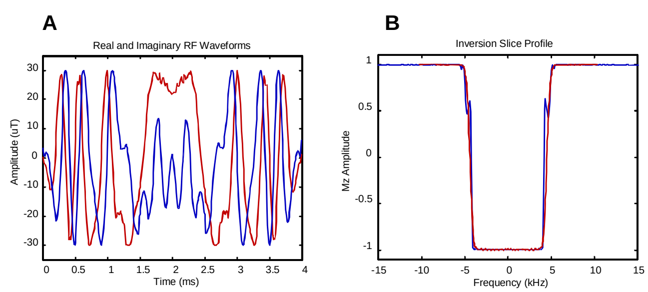

Fig. 2. A Inversion pulse. B Profiles of inversion and HS2 pulses.

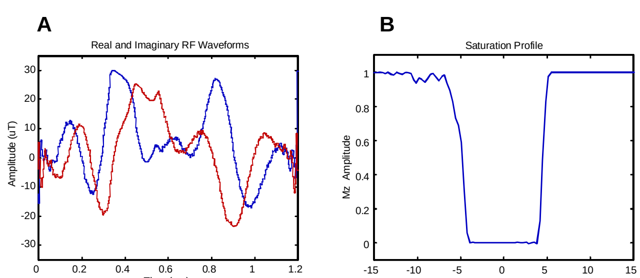

Fig. 3. A Saturation pulse. B Resulting one-sided profile.

References:

1. D.A. Yablonskiy et al., Magn Reson Med 39, 169, 1998.
2. L.G. Kaiser et al., J Magn Reson195,67,2008.
3. R.A. Edden, P.B. Barker, Magn Reson Med 58, 1276, 2007.
4. S. Conolly et al., IEEE Trans Med Imaging 2, 106, 1986.
5. J.B. Murdoch et al., J Magn Reson 74, 226, 1987.
6. J. Pauly et al., IEEE Trans Med Imaging 10, 53, 1991.
7. T.E. Skinner et al., J Magn Reson 167, 68, 2004.
8. K. Kobzar et al., J Magn Reson 170, 236, 2004.
9. T.E. Skinner et al., J Magn Reson 163, 8, 2003.
10. G.B. Matson, Magn Reson Imag 12, 1205, 1994.
11. R.F. Schulte et al., J Magn Reson 190, 271, 2008.
12. R.F Schulte et al., J Magn Reson 186, 167, 2007.
13. A. Tannus, M. Garwood, NMR Biomed 10, 423, 1997.