STABLE-2: A shorter, more B0-insensitive option for adiabatic slice-selective excitation

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Introduction: Adiabatic RF pulses are a powerful tool to achieve uniform excitation in the presence of a non-uniform B_1 field. Although many alternatives exist for slice-selective adiabatic 180° pulses to refocus or invert magnetization, options for slice-selective adiabatic excitation are more limited [1-3], and require high RF and/or gradient amplitude. A Slice-selective Tunable-flip AdiaBatic Low peak-power Excitation (STABLE) pulse was introduced in 2008 [4] which consists of an oscillating gradient in conjunction with a BIR-4-like RF envelope that is sampled by many short spatial subpulses in order to achieve spatial selectivity. The pulse functions within gradient and RF amplifier limits of current commercial clinical scanners. However, the long pulse duration of 21 ms and limited off-resonance immunity of 80 Hz make the pulse unsuitable for use in many pulse sequences and in the presence of increased B_0-inhomogeneity at higher field strengths. We have presented data from an optimized 15-ms variant of the pulse at [5], however, an experimental rather than systematic method was used to design the spectral envelope. In this work, we have used an adiabatic SLR [6] spectral RF pulse envelope in order to reduce the STABLE pulse duration and increase the off-resonance immunity. Our redesigned STABLE (STABLE-2) pulse has duration of 9.8 ms and off-resonance immunity of 120 Hz. Phantom and *in vivo* experiments demonstrate that the pulse is insensitive to a 50% variation in B_1 field amplitude.

Method: Our first step was to design a more uniform spectral adiabatic BIR-4 pulse envelope in order to reduce the peak RF amplitude of final STABLE-2 pulse. We used the adiabatic SLR technique described in [6] to generate an adiabatic full passage pulse. The adiabatic SLR method allows the pulse designer to apply additional quadratic phase across the pulse profile in order to achieve a more uniform distribution of RF energy. A highly truncated version of this full passage pulse was divided into two half passage segments. As in the conventional BIR-4 design, the spectral envelope was made up of four adiabatic SLR half-passage segments, with the first and the third segment being time-reversed. The subpulses used for spatial selectivity were windowed sinc pulses with a time-bandwidth product of 3. The number of subpulses was chosen to faithfully sample the spectral envelope while maintaining long enough subpulse duration to allow accrual of sufficient gradient area to achieve a slice thickness of approx 5 mm. Nearly triangular gradient lobes and VERSEd [7] subpulses were used to limit the gradient slew rate in order to remain below gradient hardware and peripheral nerve stimulation limits. The final pulse had a duration of 9.8 ms, maximum peak RF amplitude at adiabatic threshold of 13 μT, 15 spatial subpulses, and slice selectivity over a 120 Hz range in off-resonance. The amplitude waveform (with the spectral envelope superimposed for illustrative purposes) and the phase and gradient waveforms for the pulse are shown in Fig. 1. The 2D spatial-spectral profile over a range of 120 Hz and 500 Hz is shown in Fig. 2 A and B (vertical cross sections yield the slice profile). The simulated slice profile behavior for a range of B_1 overdrive factors (B_1 amplitude with respect to adiabatic threshold) is shown in Fig. 2 C. The fidelity of the slice is maintained over a 50% range in B_1, at which point signal loss appears at the center of the profile due to the subpulses becoming overdriven.

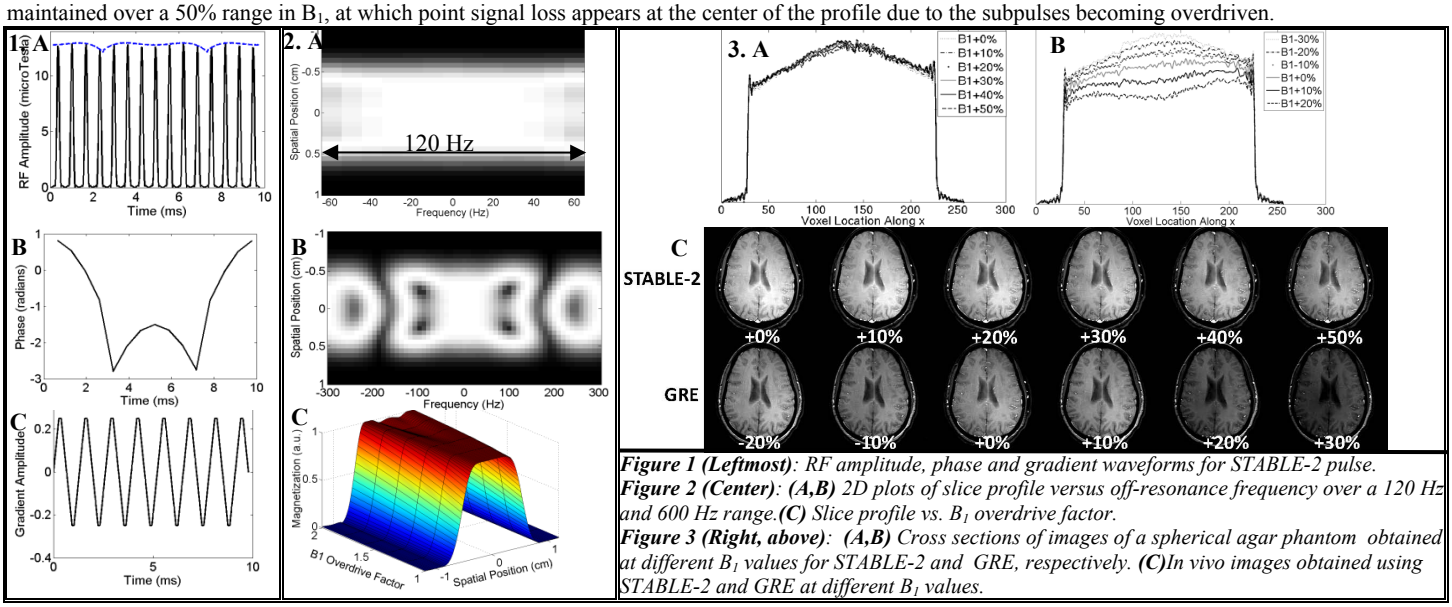

***Figure 1 (Leftmost)**: RF amplitude, phase and gradient waveforms for STABLE-2 pulse.*
***Figure 2 (Center)**: **(A,B)** 2D plots of slice profile versus off-resonance frequency over a 120 Hz and 600 Hz range.**(C)** Slice profile vs. B_1 overdrive factor.*
***Figure 3 (Right, above)**: **(A,B)** Cross sections of images of a spherical agar phantom obtained at different B_1 values for STABLE-2 and GRE, respectively. **(C)**In vivo images obtained using STABLE-2 and GRE at different B_1 values.*

Results: Figure 2 A shows cross-sections of several images of a spherical agar phantom obtained using the STABLE-2 pulse in a GRE sequence to excite a 5 mm slice (TE/TR=10/500 ms) at 3T (GE MR 750 Whole Body Magnet). The STABLE-2 pulse was scaled, in increments of 10%, to 50% above the RF adiabatic threshold amplitude. A similar experiment was conducted using a standard GRE sequence with a SLR pulse scaled to -30% to +20% of the nominal pulse amplitude (set at prescan). When compared the GRE sequence, the STABLE-2 image cross-sections remained largely invariant as B_1 was changed. Fig. 3 shows axial images of the brain of a normal volunteer obtained at 3T using the STABLE-2 pulse in a GRE sequence to excite and image a 5.5 mm slice (TE/TR=10/300 ms). Several such images were obtained with the STABLE-2 pulse scaled from 0% to 50% above the adiabatic threshold. Images were also obtained using the GRE sequence with B_1 scaled from -20% to +30% of the nominal pulse amplitude. The STABLE-2 images, shown in Fig. 3 C, exhibit minimal change in SNR and contrast at different B_1 values, while the GRE images suffer from significant signal and contrast variation.

Discussion: Phantom and *in vivo* data demonstrate that STABLE-2 performs adiabatically over 50% change in the B_1-amplitude. The pulse is better suited than the previously proposed STABLE pulse [4] for imaging at high magnetic fields, such as 7T, due to increased robustness to B_0-shifts and a shorter pulse duration enabling shorter echo times. Experiments to obtain high resolution images of the brain at 7T using the STABLE-2 pulse are underway. The distortions in off-resonance profile shown in Fig. 2 B could also be leveraged to eliminate signal from specific metabolites, such as lipids. Using the pulse for fat suppression by placing a null in the off-resonance profile on the lipid frequency is currently being investigated.

References: [1] Johnson J, et al. *J. Mag Reson*. 1989; 81:653-660. [2] de Graaf RA et al. *MRM.* 1996; 35:652–657. [3] Hsu EW et al. *MRM.* 1998;40:334–340. [4] Balchandani P. et al. *MRM.* 2008; 59:1072-1078. [5] Balchandani, et al. ISMRM Annual Meeting, Toronto, May 2008. [6] Balchandani P. et al. *MRM.* 2010; 64(3): 843-851. [7] Conolly et al. *JMRI.* 1988; 78(3): 440-458. **Acknowledgements**: Lucas Foundation, NIH R01 MH080913, NIH-NINDS K99NS070821, NIH P41 RR09784, and GE Healthcare. Thanks to Dr. Gary Glover for helpful discussions.