Slice-selective Tunable-flip AdiaBatic Low peak-power Excitation (STABLE) pulse

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Introduction: Adiabatic pulses are useful in achieving uniform excitation profiles in the presence of B_1 inhomogeneity. BIR-4 pulses [1, 2] have been shown to achieve adiabatic excitation with user-selectable flip angles. However, these pulses are neither spatially nor spectrally selective. The BIR-4 pulse design has been extended through the use of gradient modulation techniques to create slice-selective adiabatic excitation pulses [3-5]. Unfortunately, these techniques require high RF amplitude, typically above the maximum output of the RF amplifiers available on most commercial human scanners. They also require high gradient amplitude and slew rate. In this work, we have developed an alternative gradient modulated approach that achieves adiabatic slice selection with significantly lower RF peak power requirements. Our Slice-selective Tunable-flip AdiaBatic Low peak-power Excitation (STABLE) pulse 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.

Method: First, an adiabatic excitation pulse with a BIR-4 pulse envelope was designed [1]. As in the conventional BIR-4 design, the pulse was made up of four adiabatic half-passage segments, with the first and the third segment being time-reversed. In contrast to the BIR-4 design, a sech/tanh amplitude/frequency modulation function was used instead of the usual tanh/tan modulation function so that the amplitude and phase variations were sufficiently slow to be accurately sampled by the chosen number of subpulses. A phase discontinuity was introduced between the first and second segments and between the third and fourth segments to produce a 90° flip angle. The resultant spectral adiabatic excitation pulse was 21 ms long and had a spectral bandwidth, or off-resonance immunity, of approximately 80 Hz. The spectral pulse was then subsampled with the number of sublobes chosen as a trade-off between adiabaticity and minimum slice thickness. The final STABLE pulse was comprised of 33, 0.64 ms-long, conventional small tip-angle subpulses scaled by the sampled values of the adiabatic envelope. The STABLE pulse was integrated into a Gradient Recalled Echo (GRE) sequence to compare it to a standard GRE sequence with a conventional windowed-sinc excitation pulse. Figures 1 A and B show the magnitude and phase of the final STABLE 90° RF pulse. The pulse is played in conjunction with the oscillating gradient waveform. In Fig. 1 C, the simulated spatial profile is shown for a range of B_1 overdrive factors above adiabatic threshold. If the nominal B_1 is set to be at the adiabatic threshold, the pulse may be overdriven by 67% (overdrive factor of 1.67) before reaching the RF peak amplitude limit of 17 μT for our 3T RF amplifier.

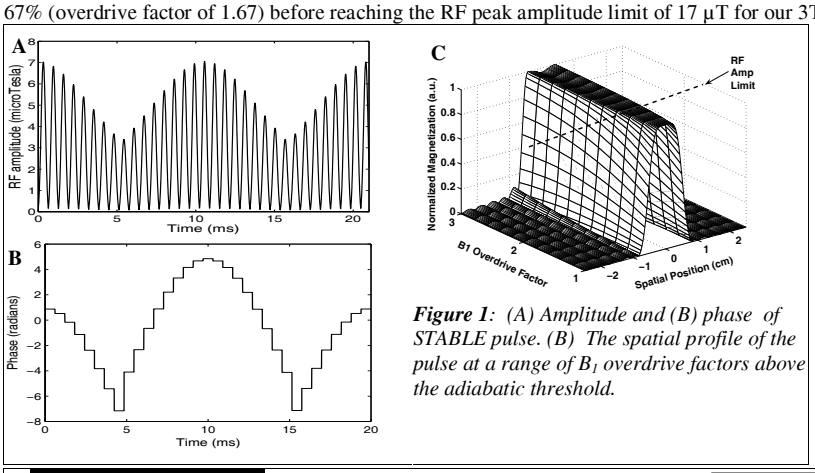

***Figure 1**: (A) Amplitude and (B) phase of STABLE pulse. (B) The spatial profile of the pulse at a range of B_1 overdrive factors above the adiabatic threshold.*

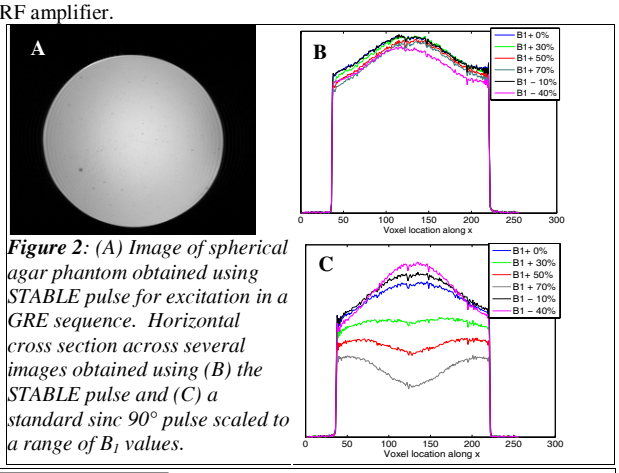

***Figure 2**: (A) Image of spherical agar phantom obtained using STABLE pulse for excitation in a GRE sequence. Horizontal cross section across several images obtained using (B) the STABLE pulse and (C) a standard sinc 90° pulse scaled to a range of B_1 values.*

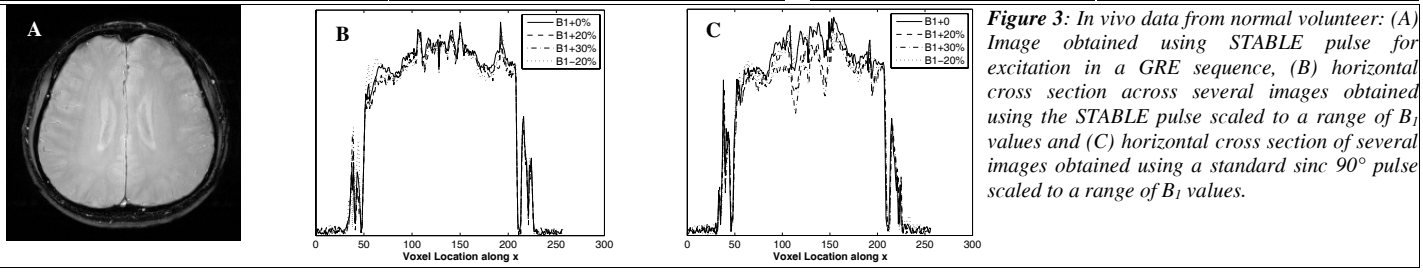

***Figure 3**: In vivo data from normal volunteer: (A) Image obtained using STABLE pulse for excitation in a GRE sequence, (B) horizontal cross section across several images obtained using the STABLE pulse scaled to a range of B_1 values and (C) horizontal cross section of several images obtained using a standard sinc 90° pulse scaled to a range of B_1 values.*

Results: Refer to Fig. 2 for data from a spherical agar phantom scanned at 3T (GE Whole Body Magnet). Figure 2 A shows an image obtained using the STABLE pulse in a GRE sequence to excite a 5 mm slice (TE/TR=13.5/500 ms). Several such images were obtained with the STABLE pulse scaled to ±60% of the nominal RF pulse magnitude (in increments of 10%). Figure 2 B shows the plots of the horizontal cross sections of these images. Adiabatic threshold is reached at around 45% below nominal peak B_1. Above the adiabatic threshold, the excited cross section remains largely invariant. The same experiment conducted using a standard GRE sequence with a conventional sinc pulse and the same sequence parameters yielded the result in Figure 2 C, demonstrating that scaling the RF caused significant variation in the image cross-section. The cross sections in Fig. 2 B are not flat due to image shading caused by the receive B_1 profile. Refer to Fig. 3 for *in vivo* data from the brain of a normal volunteer scanned at 3T. Figure 3 A shows an image obtained using the STABLE pulse in a GRE sequence to excite and image a 5 mm slice. Several such images were obtained with the STABLE pulse scaled from -20% to +30% of the nominal RF pulse magnitude. Figure 3 B shows the plots of the central horizontal cross sections of these images, demonstrating minimal variation of the cross-sectional profile as B_1 is varied. Of the variation that does occur, some portion may be attributed to patient motion between scans. Cross-sections obtained when B_1 is varied for a standard GRE sequence are shown in Fig. 3 C.

Discussion: Phantom and *in vivo* data demonstrate that the STABLE pulse is slice-selective as well as adiabatic over at least a 50% change in B_1 while remaining within the RF peak amplitude limit of 17 μT for our 3 T scanner. STABLE pulses may be designed to achieve arbitrary flip angles by adjusting the phase discontinuity introduced between the pulse segments. The magnetization vector is mainly spin-locked perpendicular to the effective field for the duration of the STABLE pulse. The magnetization vector in this state undergoes $T_{2\rho}$ relaxation. Also, the spin-locked state of the magnetization for the duration of the pulse results in the suppression of T_2* decay. These factors contribute to the unique contrast achieved by the STABLE pulse. Future work is focused on finding the optimal amplitude and frequency modulation functions for the STABLE adiabatic envelope so that sampling errors may be minimized.

References: [1] Staewen R. S., et al. *Invest. Radiol. 1990;* 25:559-567. [2] Garwood M., et al. *J. Magn. Reson. 1991;* 94: 511-525. [3] Johnson J., et al. *J, Magn. Reson. 1989;* 81: 653-660. [4] de Graaf R. A., *Magn. Reson. Med. 1996;* 35: 652-657. [5] Hsu E. W., *Magn. Reson. Med.* 1998 Aug; 40 (2): 334-40.

Acknowledgements: Lucas Foundation & NIH RR09784