Design of high-bandwidth adiabatic RF pulses using the Shinnar Le-Roux algorithm

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Introduction: Adiabatic pulses are a special class of RF pulses that provide B_1-insensitive rotation of the magnetization. When utilizing adiabatic pulses, particularly at high magnetic fields, low-SAR pulse designs are highly desirable. In this work, we present a new, systematic method for designing high-bandwidth, low-peak-amplitude adiabatic pulses by using the Shinnar Le-Roux (SLR) algorithm [1] for pulse design. Currently, the SLR algorithm is extensively employed to design non-adiabatic pulses for use in MR imaging and spectroscopy. We have adapted the SLR algorithm to create RF pulses that also satisfy the adiabatic condition over the desired spectral profile. An interesting characteristic of adiabatic pulses is that they generate a spectral profile with quadratic phase. By overlaying a sufficient amount of quadratic phase across the spectral profile prior to the inverse SLR transform, we were able to generate RF pulses that exhibited the required spectral characteristics as well as adiabatic behavior. The use of the SLR algorithm to produce non-adiabatic quadratic-phase RF pulses has been previously proposed [2]. Our method employs quadratic phase in a similar manner to distribute RF energy and reduce SAR, while maintaining adiabaticity.

Method: The SLR algorithm reduces the problem of pulse design into that of designing two polynomials, α and β, which may be reversibly transformed to yield the RF pulse. We first find the β polynomial for the adiabatic RF pulse. The real part of the desired profile, F(ω), is generated using the `firls` function in Matlab. In this step, parameters such as ripple requirements, bandwidth (BW) and transition width are specified. Once the FIR filter is calculated, the sample period of the final pulse, ΔT, or equivalently the spectral BW, is chosen. The chosen BW is limited by the fractional transition width. Low spectral BW will limit the amount of quadratic phase that may be applied before truncation of the RF pulse occurs. The inverse Fourier Transform (FT) of the FIR filter produced by the `firls` function is set to be the real part of the spectral profile, $F_{real}(\omega)$. Quadratic phase is overlaid on the real part of the spectral profile to yield the final F(ω): $F(\omega) = F_{real}(\omega) e^{ik\pi^2\omega^2}$. Limits for the parameter k, which determines the amount of applied quadratic phase, were found empirically. Increasing the k value distributes RF energy more evenly, resulting in lower overall SAR. A k value that is too large degrades the slice profile while a k value that is too low results in the distortion of spectral profile at low B_1 values. The β polynomial is given by the FT of the spectral profile F(ω). A matched minimum-phase, minimum power α polynomial is then calculated [1]. Once α and β are specified, they are set as inputs to the inverse SLR transform to yield the final RF waveform. The amplitude and phase waveforms and the simulated spectral profile over a range of B_1 values for an exemplary adiabatic SLR pulse are shown in Figs. 1 A, B and C.

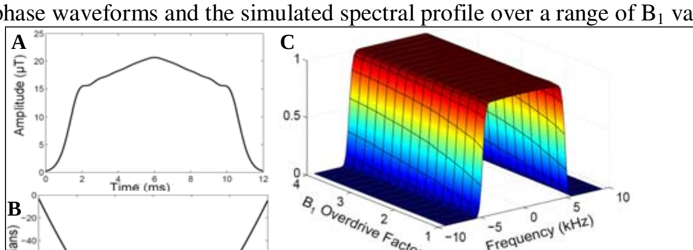

Figure 1: (A) Amplitude and (B) phase of adiabatic SLR pulse. (C) The spectral profile of the pulse at a range of B_1 overdrive factors above the adiabatic threshold.

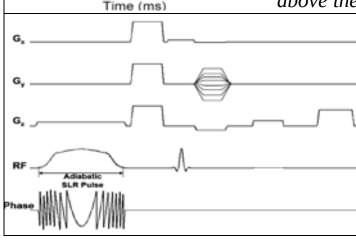

Figure 2: RF, phase and gradient waveforms for the pulse sequence which uses the adiabatic SLR pulse for inversion. An image is acquired with the inversion pulse turned on and subtracted from an image acquired with the inversion pulse turned off. In the subtracted image, only the inverted slice will appear bright.

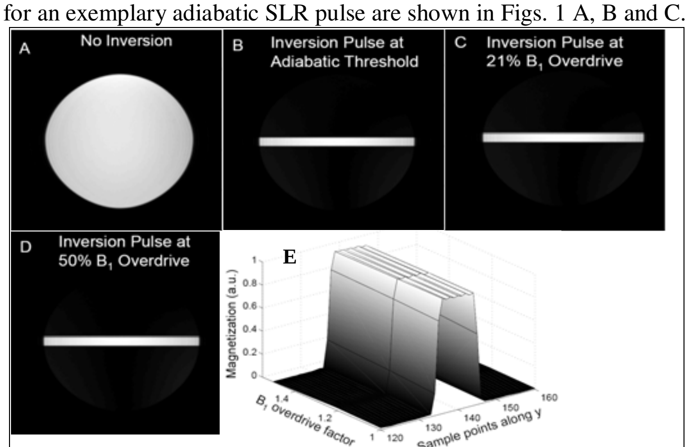

Figure 3: Results obtained from a spherical agar phantom using the pulse sequence in Fig. 2. Image of a slice with (A) adiabatic inversion pulse turned off. Images of same slice with inversion pulse played at (B) the adiabatic threshold, (C) 21% and (D) 50% above the adiabatic threshold, subtracted from image in (A).(E) Cross section of phantom images vs. B_1

Experiments: Phantom experiments were conducted using a 1.5T MR scanner to validate the pulse performance. A 5 kHz adiabatic SLR pulse was added to a standard GRE sequence as an inversion pulse prior to the 90° excitation pulse as shown in Fig. 2. A slice-selective gradient was played in conjunction with the pulse. Frequency and phase encoding dimensions were set to be orthogonal to the slice-select dimension in order to provide an image of the inversion slice profile. Images were obtained of the spherical water phantom with the inversion pulse amplitude set to the nominal B_1 (at the adiabatic threshold), 21% above nominal B_1 and 50% above nominal B_1. These were subtracted from an image obtained without the adiabatic inversion pulse. Acquisition parameters were: TE/TR= 9/5500 ms, matrix size = 256x128 and scan time = 11:44 min.

Results: See Fig. 3 for images obtained for the acquisition (A) without the inversion pulse, and with the inversion pulse at (B) adiabatic threshold, (C) 21% above the adiabatic threshold and (D) 50% above the adiabatic threshold. Vertical cross-sections through the center of these images are plotted against B_1 in Fig. 3 E. Profiles are largely invariant for different values of B_1 illustrating adiabatic behavior.

Discussion: In this work the first design algorithm that uses the SLR transform to generate adiabatic pulses is presented. Simulations and phantom experiments demonstrate that the pulses generated using this new method behave adiabatically. Pulses designed using numerically optimized modulation functions [3] or modulation functions that satisfy offset-independent adiabaticity [4] have been proposed to broaden the BW of adiabatic pulses while minimizing the RF power. Our method enables the pulse designer to explicitly design the spectral profile and determine the degree of quadratic phase prior to using the inverse SLR transform to generate the corresponding adiabatic RF pulse.

References: [1] Pauly J, et al. *IEEE TMI* 1991; 10(1):53–65. [2] Schulte RF, et al. *J Magn Reson* 2004;166(1):111–122. [3] Ugurbil K, et al. *J Magn Reson* 1988; 80:448–469. [4] Tannus A, Garwood M. *J Magn Reson* 1996;120:133–137.

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