Gradient offset independent adiabatic pulses for high-field MR spectroscopy on clinical scanners

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Abstract:

Adiabatic pulses are necessary to mitigate chemical shift artifact (CSA) and rf inhomogeneity at high-field MRS, but often they need longer durations (≥ 5 ms) and higher rf strengths (> 1 kHz) that limits their application in-vivo. Gradient offset independent adiabatic (GOIA) pulses have been proposed [1] as an elegant solution to reduce these requirements while effectively increasing the excitation bandwidth (> 20 kHz). Although GOIA has similar principles with VERSE (variable-rate selective excitation) pulses [2], GOIA has the advantage of a constant adiabatic factor over the entire spectrum. Despite of the benefits, their use on clinical scanners has not been widespread. Here we report on a new class of GOIA pulses derived from WURST [3] adiabatic pulses. We present numerical simulations and experimental results obtained on phantoms and human volunteers on whole-body 3T and 7T Tim Trio clinical scanners (Siemens, Erlangen).

Introduction:

Chemical shift artifact is inversely proportional to the bandwidth (BW) of the rf pulse used for signal localization, thus increasing pulse bandwidths is highly desirable for MRS and MRSI applications. In general, a 5% displacement is considered acceptable for MRS/MRSI [4]. To achieve this at 7T over the 3.8 ppm 1H spectral range of interest a BW of 20 kHz is necessary. This would translate to only 5 mm displacement for a typical VOI of 10 cm in MRSI compared to 2 cm or more using conventional adiabatic pulses that are practically limited to BW of 5-6 kHz. We sought GOIA pulses that have BW = 20 kHz, are shorter than 5 ms and require less than 1 kHz peak rf amplitude. In particular, we designed pulses that are 3.5 ms (R = 70) and 4ms (R = 80) long and require 0.8 kHz or 0.7 kHz strengths, respectively. WURST (W8) [3] and HypSech (HS8) [5] have been used as starting classes. Localization with time varying gradients has been employed using inverse WURST (W4) and HypSech (HS4) modulation functions. These pulses (named GOIA-W84 and GOIA-HS84) compare favorably to FOCI [6] pulses of the same bandwidth and length which instead require 1.4 kHz maximum rf strength. In addition, constant adiabaticity is insured over the entire bandwidth for GOIA pulses while for FOCI and conventional adiabatic pulses the adiabatic condition degrades away from the center of the bandwidth.

Numerical simulations:

Performance of the GOIA-W84, GOIA-HS84 and FOCI pulses has been simulated using GAMMA [7] environment. Phase modulation of GOIA has been implemented by numerical integration of the constant adiabaticity equation [1]:

$$d\left(\Delta\omega(t)\right)/dt - \left[\Delta\omega(t)/G(t)\right] d\left(G(t)\right)/dt = B_1^2(t)/K$$

where $\Delta\omega(t)$, $G(t)$ and $B_1(t)$ represent the driving functions for offset, gradient and rf amplitude, respectively, and K is a constant that depends of the adiabatic quality factor.

Figure 1 presents the driving functions for GOIA-W84 which has been found to provide the best slice profile and SNR. Slice profiles for the double refocusing adiabatic full passage (AFP) [2] with GOIA-W84 have been calculated at 3T for on-resonance (black) and ± 1.5 ppm (red, green) offsets. A spectrum for NAA, Choline, Creatine (only the CH3) and Lactate (coupled CH and CH3) spin systems has been simulated under a symmetric LASER [8] sequence using GOIA-W84 pulses (BW = 20 kHz, 3.5 ms, 0.8 kHz peak rf amplitude) at 3T and TE = 50 ms.

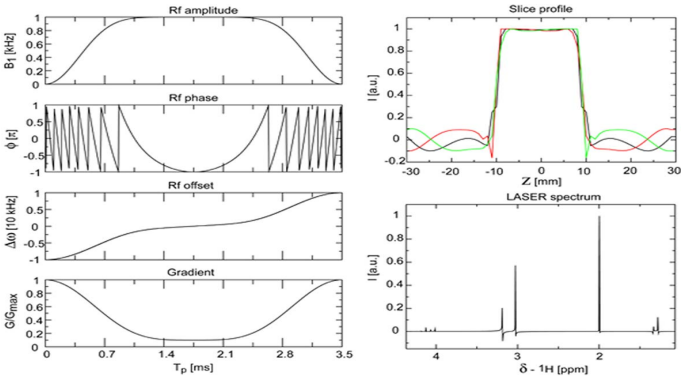

Figure 1. GOIA-W84 modulations, simulated slice profile and spectrum.

Experimental results:

The designed pulses have been tested on phantoms and volunteers at 3T (Tx body / Rx head matrix coils) and 7T (de-tunable Tx/Rx birdcage coil of 28 cm diameter). Slice profiles have been measured with a spin echo (TE = 50 ms) sequence using double refocusing AFP [2]. Comparison of slice profiles at 3T (Fig. 2) between GOIA-W84 (3.5 ms, BW = 20 kHz, 0.8 kHz peak rf amplitude) and Sinc4 (Mao [9], 2.6 ms, BW = 2.1 kHz, 1 kHz peak rf amplitude) indicates better localization (sharper boundaries) and more uniform excitation (flatter top) for the first. Single voxel spectra (SVS) have been measured at 3T and 7T on phantoms and volunteers with PRESS [10] and LASER [8] sequences using the above pulses. Figure 2 presents phantom spectra with an increase in SNR of up to 50% for a TE of 50 ms and up to 25% for a TE = 30 ms. Spectra measured on volunteers (TE = 50 ms, Fig. 3) show an SNR improvement of 30% at 3T and almost 100% at 7T. Minimum TE possible in our implementation with 3.5 ms pulses can be as low as 27 ms, but a small delay (up to TE = 30 ms) can reduce eddy current effects.

Discussions:

SVS results indicate an SNR increase when using GOIA-W84. The increase in SNR becomes greater at longer TE due to more favorable T2 relaxation in the rotating frame (T2ρ) under the LASER rf pulse train as compared to T2 relaxation under PRESS (T2ρ > T2), as has been recognized [8]. Hence, an increase in TE has lesser penalty. A closer look reveals also sharper lines which are consistent with a better defined voxel. Required rf strength is well bellow the SAR and practical limits. A further increase above the adiabatic threshold is possible and can help to alleviate the problem of rf inhomogeneity, as it is apparent at 7T. This is not possible for Sinc4 or FOCI that were already at maximum. These characteristics are of even greater importance for CSI which is currently under testing. Further development includes extension of this method to parallel transmit arrays [11] to improve the volume selection or to lower the SAR requirements.

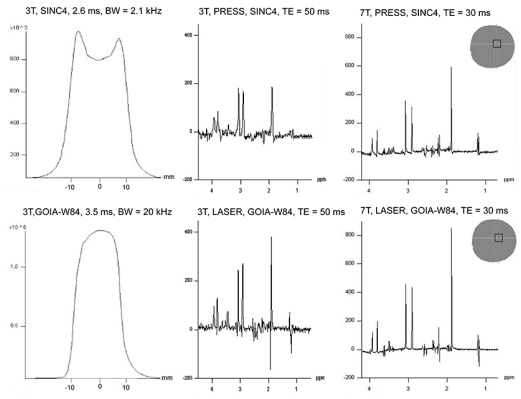

Figure 2. Phantom: slice profiles (left) and SVS (right).

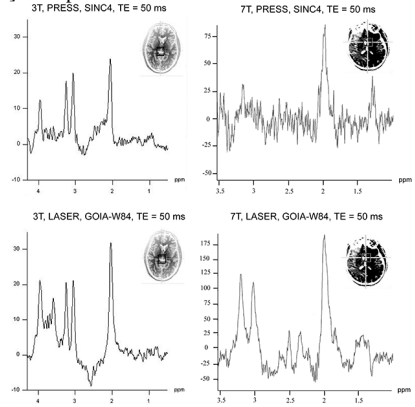

Figure 3. Volunteer: SVS at 3T and 7T.

References:

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