Minimum-Duration Adiabatic Spectral-Spatial Refocusing Pulses

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Introduction: B_1-insensitive or adiabatic spectral-spatial RF pulses can be designed by weighting successive spatial sublobe pulses with a frequency-swept modulation [1]. This approach has been used with a hyperbolic secant modulation [2] to design the two refocusing pulses in PRESS-localized spectroscopic imaging sequences [3-5] for application at high-field where B_1 homogeneity is a concern. We present a method using an alternative frequency-sweep modulation that can substantially shorten the duration of the refocusing pulses and thereby enable much shorter echo times.

Methods: The problem of designing an adiabatic spectral-spatial RF pulse is first separated into the determination of the spatial and spectral weighting functions. The minimum-duration gradient sublobe is first designed subject to the desired spatial RF time-bandwidth, gradient system limitations and the percentage of the sublobe ramps on which the RF pulse will be VERSE'd [6]. A linear-phase sublobe RF pulse is then designed using the SLR algorithm to yield the desired spatial profile, passband and stopband ripples [7]. The temporal weighting for a given duration pulse is designed using HSn modulation [8,9]. The normalized HSn magnitude is $F_1(\tau) = \mathrm{sech}(\beta\tau^n)$ where β=5.3 and τ = [-1…1], while the frequency sweep is numerically derived as in [9]. The individual sublobe RF pulses are then weighted by the samples of the HSn modulation taken at the midpoint of each sublobe.

The M_{xy} refocused by the spectral-spatial pulse is then calculated for an on-resonant spin at isocenter for a range of peak B_1 values and HSn time exponent n values. The minimum n that provides satisfactory refocusing over a desired range in B_1 is then selected.

Results: An 11.7-ms refocusing spectral-spatial pulse was designed to provide a 4-cm thick slice with time-bandwidth of 2 and passband/stopband ripples of 0.01 subject to gradient system limits (4 G/cm, 15 G/cm/ms) and a VERSE limit of 50% of the sublobe ramps. Figure 1 shows the refocused M_{xy} dependence on peak B_1 and HSn time exponent for pulses designed to provide a) 400-Hz or b) 700-Hz spectral BW. The large oscillation in M_{xy} in Fig. 1a is an indication the sweep rate is too high, causing a loss of spin-lock [9]. Fig. 1b shows full refocusing is achieved for a 700-Hz pulse for n = 3.5 and peak B_1 of 0.16G. If this pulse is overdriven by 25% the peak B_1 is 0.2G.

Figure 2c shows the RF magnitude and gradient for the 25% overdriven HS3.5 RF pulse together with a 25% overdriven HS1 pulse (Fig. 2a). To meet a peak B_1 requirement of < 0.2G, the HS1 pulse duration must be 26 ms. The HS35 total pulse power is 45% greater than the HS1 pulse. Figures 2b and 2d show the respective spectral-spatial spin-echo profiles following two refocusing pulses applied on X and Y. Figure 3 shows a comparison of the simulated spin-echo profiles for the 11.7-ms HS3.5 with the experimental profiles acquired on a GE Signa 1.5-T scanner. The adiabatic nature of the pulse is illustrated by scaling the RF pulse to 80%, 100% and 120% of the nominal 25% overdriven amplitude and all show good agreement.

Discussion: A novel approach to optimize adiabatic spectral-spatial refocusing pulses for minimum duration has been presented. The pulses are shown to provide adiabatic behavior over a range of 80-120% the nominal peak amplitude, making them appropriate for high-field applications. The example shown provides a 55% reduction in pulse duration, though SAR would increase by 45%. The HSn pulses also have much larger spectral transition bands, and higher passband ripple due to operating close to the adiabatic condition. Increasing the duration of the pulse and thereby going to smaller HSn time exponents can trade off these issues.

References: [1] Conolly *et al.*, MRM, 24:302–13, 1992. [2] Silver *et al.*, Phys. Rev. A, 31:2753–55, 1985. [3] Cunningham *et al.*, Proc. ISMRM, p72, 2007. [4] Balchandani *et al.*, MRM, 59(5):973–979, 2008. [5] Xu *et al.*, MRI, 26(9):1201–6, 2008. [6] Pauly *et al.*, IEEE TMI, 10(1):53–65, 1991. [7] Conolly *et al.*, J Mag Res, 78:440–458, 1988. [8] Tannu's *et al.*, J Mag Res. Series A, 120:133–7, 1996. [9] Garwood *et al.*, J Mag Res, 153(2):155–77, 2001.

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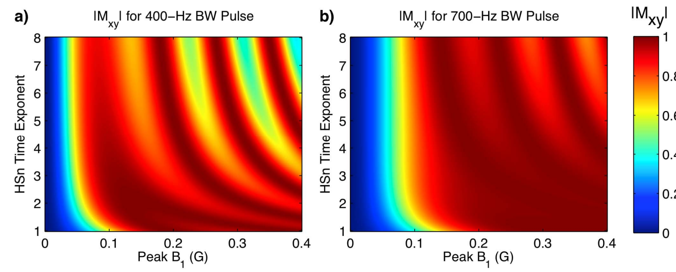

Figure 1: Dependence of refocused M_{xy} for an 11.7-ms spectral-spatial pulse as a function of peak B_1 and HSn time exponent for an isocenter on-resonant spin. Nominal spectral bandwidth was a) 400Hz b) 700Hz.

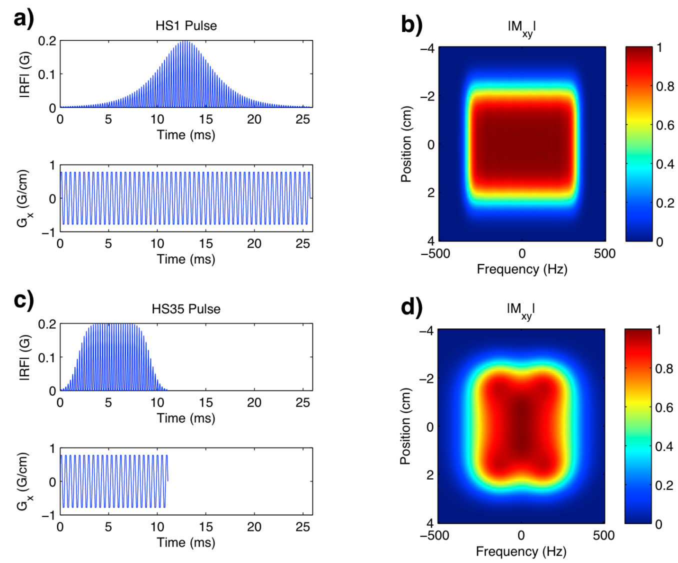

Figure 2: a) HS1 and c) HS3.5 spectral-spatial refocusing pulses and their spin-echo profiles b) and d) following application of two pulses (as in a PRESS sequence).

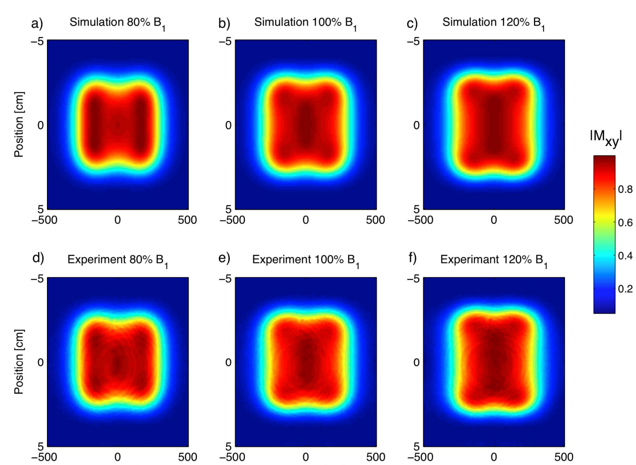

Figure 3: Comparison of simulated and experimentally acquired spin-echo profiles after application of two HS3.5 refocusing pulses.