SLR Pulse Implementation in Multi-Slice 2D FLASH Pulse Sequence for 3T MRI and Beyond

A Alhamud[1], Jay Moore[2], Neal Derman[1], Ernesta Meintjes[1], and Marcin Jankiewicz[1]

[1]*Human Biology,MRC/UCT Medical Imaging Research Unit, University of Cape Town, Cape Town, Western Cape, South Africa,* [2]*Institute of Imaging Science, Vanderbilt University, Nashville, TN, United States*

Target Audience: Imaging scientists interested in optimization and design of RF pulses with built-in $|B_1^+|$-ΔB_0 insensitivity and improvement of data quality.

Purpose: We show how a class of B_1^+-insensitive excitation pulses, generated with Shinnar-Le Roux (SLR) algorithm [1] improves the performance (measured in terms of SNR) of a FLASH (spoiled gradient echo) sequence. We present results of in-vivo-experiments utilizing a train (a composite waveform) of SLR pulses with a simultaneous slice-selection (e.g. [2]) or slice-selective realization of adiabatic BIR-4 [3].

Methods: A 6.5 ms time-bandwidth 4-subpulse was designed to excite 90° flip-angle (FA) with the maximum amplitude set to 11µT, with pass/stopband ripples of 0.01°/0.5°, for a typical range of $|B_1^+|$-ΔB_0 inhomogeneities in human head at 3 Tesla, i.e. 0.7-1.2 for $|B_1^+|$ (in units of nominal FA) and ±150Hz for ΔB_0. It is further assumed that the slice-selective gradient waveform (set to 4mm slice thickness) is a conventional SLR and subject to a similar optimization as excitation pulses. The $|B_1^+|$-insensitive pulse was implemented on a Siemens Allegra 3 T scanner (Siemens Healthcare, Erlangen, Germany) with a single-channel coil and replaced the excitation part of the FLASH sequence. Multi-slice scan was performed with both the standard 3.2ms *sinc* (Figure 1 (bottom)) and the new 6.4ms composite pulse (Figure 1 (top)). $|B_1^+|$ (double-angle method, α=30°, TR/TE=5000/5.9ms) and ΔB_0 (ΔT_E=2.5ms) were acquired at the same resolution to assist the pulse-performance analysis. The acquisition parameters for the standard and the modified sequences were: slice thickness = 4mm, matrix size 128x128, FA = 90°, TR/TE = 5000/5.9 ms, number of slices = 9.

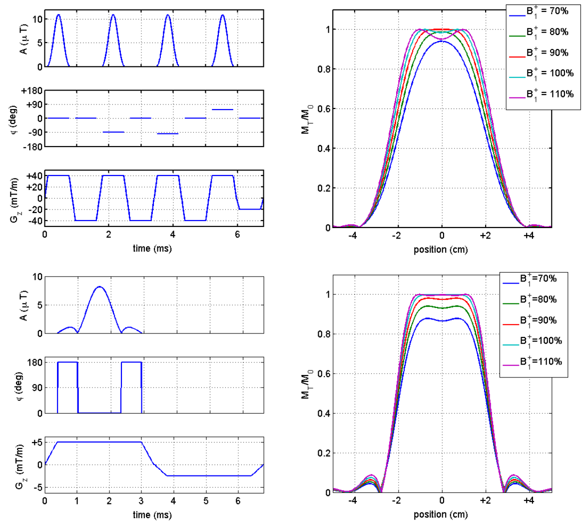

Figure 1. *Amplitude and phase modulated waveforms of the FA=90°, 6.5 ms $|B_1^+|$-insensitive composite (4 SLR sub-pulses) pulse (top left) together with its slice selective-gradient waveform. Transverse magnetization profiles excited by that pulse (for different values of RF inhomogeneities) are shown on the top right. The excitation pattern is flat across the slice for different $|B_1^+|$values and outperforms [5] standard sinc pulse (bottom)*

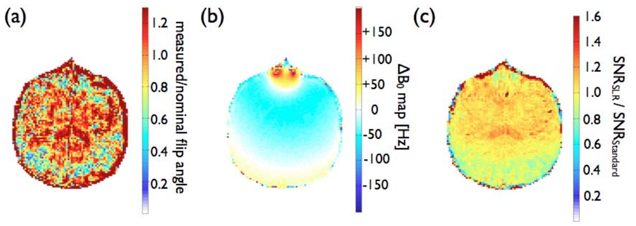

Figure 2. $|B_1^+|$ distribution for the iso-central slice (a). Corresponding ΔB_0 map (b). Ratio of SNR values for the composite waveform (SNR_{SLR}) to standard FLASH sequence ($SNR_{standard}$) (c) show up to 60% increase in SNR in off-resonance and $|B_1^+|$ challenging regions. The SNR drop-out is due to differences in slice profiles (in favour of standard sequence).

Results: Figure 1 (left) plots the amplitude and phase modulation waveforms for a 90° excitation part of 2D FLASH sequence for both *sinc* and composite slice-selective SLR pulses. The optimized slice-selective gradient waveform resembles a balanced series of gradient trapezoid (40mT/m, 133T/m/s), while the amplitude modulated waveform resembles a train of SLR slice-selective pulses. Figure 1 (right) plots the simulated transverse magnetization excited by the composite and *sinc* pulse for various levels of $|B_1^+|$ inhomogeneities typical in 3 Tesla human-head imaging. Results ($|B_1^+|$-ΔB_0 field map, shown on Figure 2 (a)-(b) and SNR gain Figure 2 (c)) were shown only for an iso-central slice as it is representative of regions with the most pronounced $|B_1^+|$-ΔB_0 variations. Signal-to-Noise-Ratios were calculated for both scenarios (SNR_{SLR} and $SNR_{standard}$ correspondingly) and divided to estimate the SNR gain (Figure 2 (c)).

Discussion: Figure 2 (c) demonstrates that SNR gain correlates with the $|B_1^+|$ map especially in the anterior and central regions. It is important to notice that in the posterior region, the composite pulse underperforms with respect to the *sinc* pulse; this is due to differences in the slice profiles (Figure 1 (right)) and their performance on-resonance, i.e. $\Delta B_0 \approx 0$, where the *sinc* pulse generates more signal. Moreover, the posterior region shows severe $|B_1^+|$ inhomogeneity (as low as 0.5) which is outside of the optimization region (0.7-1.2) where performance of the composite pulse drops dramatically (this is consistent with previous findings [4]).

Conclusion: We have evaluated the performance of the $|B_1^+|$-insensitive excitation pulses designed from a rotated SLR algorithm. They excite a target FA (set here to 90°) over a prescribed $|B_1^+|$-ΔB_0 range with minimum sub-pulse duration. These pulses therefore represent an alternative to slice-selective adiabatic pulses such as BIR-4 [4]. Limited time penalty (short TR) opens new avenues for applications in challenging imaging scenarios and applications (fMRI, DTI through modification of the excitation component of EPI sequences).

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References: [1] J. M. Pauly *et al*, IEEE TMI, 10:53, (1991); [2] W.A. Grissom *et al*, MRM 62(5):1242 (2009); [3] Balchandani et al, MRM:59(5), 1072 (2008). [4] J. Moore, M. Jankiewicz *et al.*, JMR: 205 (2010);