LOW-TIDE: Linear Filter Based Optimal Window Transition to Driven Equilibrium for b-SSFP Sequences

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Introduction: A Linear filter-based Optimal Window Transition to Driven Equilibrium (LOW-TIDE) approach to catalyzing the steady-state signal during continuous acquisition of image data in balanced SSFP [1] is presented here. While TIDE [2] follows an almost linear flip angle evolution scheme, it has been shown in the context of a ramp up sequence that the component perpendicular to the axis of rotation of magnetization can be expressed as a Discrete Fourier Transform of the first difference of the nutation angle sequence [3]. This lends itself classically to the use of linear filtering theory to reduce side lobe response over a frequency range which in turn translates to smaller signal fluctuations. Three different windows (Kaiser-Bessel, Blackman-Harris and Chebyshev) were examined and compared with linear ramp down and TIDE. Based on simulations, all three windows were found to generate flip angle schemes superior to TIDE. Of the three schemes, the Blackman-Harris window seemed most attractive based on a theoretical figure of merit and ease of implementation. All schemes were implemented in a b-SSFP sequence modified to allow for image data acquisition during transition to steady-state. Comparison results are presented.

Materials and Methods: Simulations were performed in Matlab® based on the b-SSFP algorithm for signal evolution as given in [4]. For the modified Kaiser-Bessel (KB) window of zeroth order, $\beta=\pi$ was used; a minimum 4-term Blackman-Harris (BH) window was implemented while the Chebyshev (CB) window used had a relative side-lobe attenuation of 140dB. A figure-of-merit (FOM) was devised which corroborated with theoretical and practical observations. The FOM is given as $\sum_{\omega}[\mathcal{C}\{\mathcal{F}^{(1)}(M(t,\omega)),\mathcal{F}^{(1)}(M(t,\omega=0))\}-\mathcal{R}\{\mathcal{F}^{(1)}(M(t,\omega=0))\}]^2/\omega$, $\omega\neq0$. The operator $\mathcal{F}^{(1)}$ denotes the 1-D Fourier transform of the time-domain magnetization signal evaluated at off-resonance frequency ω, $\mathcal{C}$ refers to the cross-correlation operator while $\mathcal{R}$ refers to the autocorrelation operator. Oscillations in the time-domain response of the magnetization signal are seen at off-resonance frequencies. This in turn results in side-peaks in the Fourier domain. Measuring the difference between the cross-correlation and the autocorrelation provides a measure of "closeness" to the ideal response . The correlation is weighted by the off-resonance frequency, with frequencies closer to on-resonance carrying a higher weight. A smaller FOM corresponds to a better magnetization response over a fixed range of off-resonance frequencies. The FOM was tested using simulations and observed responses to parameter changes. For example, increasing T2 while maintaining constant TR, T1 and flip angle increases signal oscillations that are reflected in larger values for the FOM. Increasing TR while maintaining constant T1, T2 and flip angle also increases oscillations and the FOM. All four preparation schemes (TIDE, K-B, B-H and CB windows) were implemented on a Philips 3T Achieva scanner (Release 1.5 software), and integrated into a user interface facilitating customizable flip angle schedules.

Results: The four transition schemes were simulated for several different values of TR/T1/T2. Sample results are presented here for a TR=7ms, T1=1550ms, T2=170ms. The flip angle schedule for a ramp down of length 30 TRs is presented for the different preparation schemes in Figure 1. A mesh plot of the signal evolution as a function of time (TRs) and off-resonance frequency (for B-H window) is shown in Figure 2. While the on-resonance signal evolution is similar for all schemes (Figure 3), cross-correlation of the frequency response (0Hz with 25Hz) shows differences (Figure 4). A smaller area under the side peaks (arrows) for B-H when compared with TIDE corresponds to smaller oscillations in the time domain response. The FOMs were evaluated over $|\omega|<1/(2\times TR)$ in steps of 1Hz and normalized to the value for the linear ramp down transition scheme. FOM values are 0.976, 0.937, 0.76 and 0.74 for TIDE, KB, BH and CB, respectively. This is in line with theoretical expectations since side-lobe suppression increases from 26dB (for KB)→93dB (for BH)→140dB (for CB). Comparable phantom images (same Rx and window/level) at 30Hz off-resonance are shown in Figure 4.

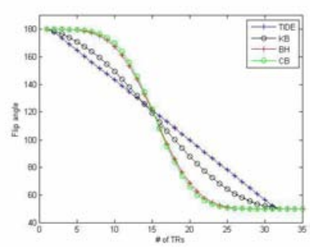

Figure1. Flip angle schedule

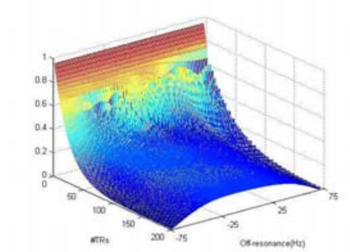

Figure 2. Signal evolution (B-H window)

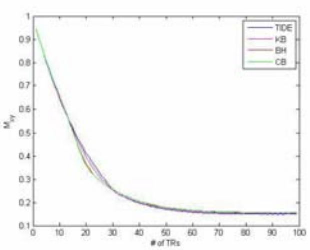

Fig. 3a: On-resonance response

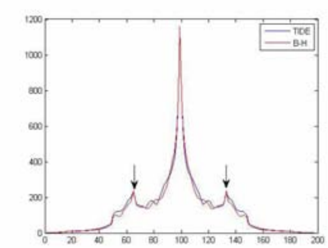

Fig. 3b: Off-resonance response

While the on-resonance response is similar for all schemes, the off-resonance response shows increased ghosting artifacts with TIDE compared with the BH window. Measurements on the entire ghost at 30Hz off-resonance gave values of 184±125 and 125±96 for TIDE and BH, respectively.

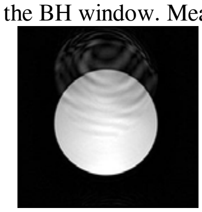

Figure4: TIDE

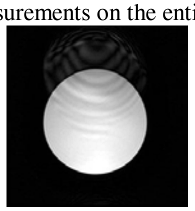

Figure 4(b): B-H

Discussion: LOW-TIDE offers improved off-resonance response for T2w-bSSFP sequences. While the Chebyshev window showed the best response, the ease of implementation and the near optimal response of the Blackman-Harris window make it most attractive for practical implementation. LOW-TIDE and related approaches may elevate the clinical utility of b-SSFP, by optimizing the contrast features of an otherwise favorably fast and efficient scan technique.

References: [1] D. Paul, M. Markl, H-P Fautz, J. Hennig, *Magn. Reson. Med.*, 56:82-93 (2006).

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