Theoretical and experimental aspects of time shared sweep excitation using HSn pulses

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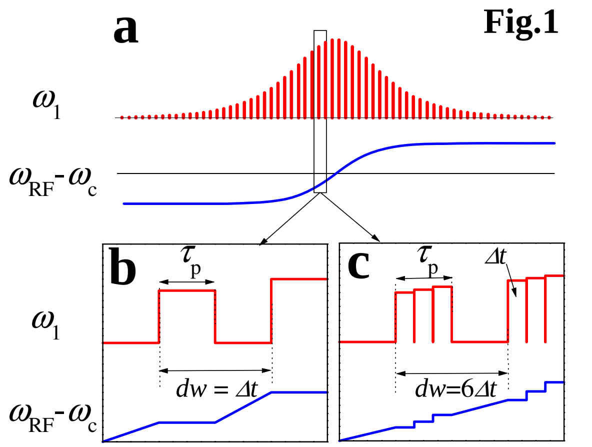
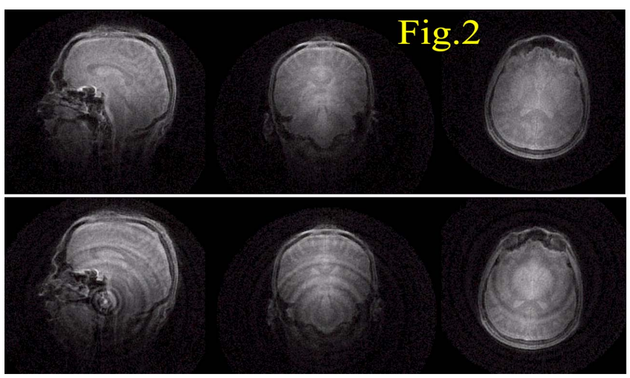
INTRODUCTION The SWIFT method (SWeep Imaging with Fourier Transform) [1] has significant benefits for studying objects with ultra fast spin-spin relaxation rates. SWIFT uses swept radio frequency (RF) excitation and virtually simultaneous signal acquisition in a time-shared mode. Correlation of the response from the spin system with the excitation pulse function is used to extract the useful signal. High quality images can be obtained provided the frequency-modulated (FM) pulse used can produce a flat broadband excitation profile. This work considers some theoretical and experimental aspects of time-shared sweep excitation in SWIFT using the FM pulses of the HSn family [2,3]. In addition, a compact approximation for flip angles of HSn pulses is presented, which allows estimation of multiple performance parameters, including peak power, RF energy and specific absorption rate (SAR) limitations of the SWIFT sequence.

THEORY The frequency and amplitude modulated RF pulses are described by function $f_{RF}(t) = \omega_1(t)exp(-j\omega_{RF}(t))$. With HSn pulses, the time dependent RF amplitude is $\omega_1(t) = \omega_{1\max} f_n(t)$ and the instantaneous frequency is $\omega_{RF}(t) = \omega_c + (B_\omega / P(n))\int_0^t f_n^2(\tau)d\tau$ where $\omega_{1\max}$ is the maximum amplitude of the RF field in rad/s, ω_c is the carrier frequency, B_ω is the bandwidth of the frequency sweep, $P(n)$ is relative pulse power and $f_n(t) = sech(\beta(2t/T_p - 1)^n)$ is the RF driving function with pulse length T_p, shape factor n, and truncation factor β.

Here we consider two factors that affect the profile of the time shared excitation used in SWIFT. The first is a discrete representation of the pulse with a finite number of pulse elements of width Δt, which modifies the theoretical excitation profile of the HSn pulse (F_{RF}) as $F^*_{RF}(\omega) = \left[F_{RF}(\omega) \oplus comb(\omega, 1/\Delta t)\right] sinc(\omega\Delta t/2)$ and creates an infinite number of sidebands. The second is a full amplitude modulation of the excitation pulse to enable making an acquisition sampling "during" the pulse which introduces an additional modification of the excitation profile as: $F^*_{RFgap}(\omega) = F^*_{RF} \oplus \left[comb(\omega, 1/dw)\, sinc(\omega\tau_p/2)\right]$. If the "transmitter on" time is labeled as τ_p, then the time with the "transmitter off" is equal to dw-τ_p with a duty cycle $d_c = \tau_p/dw$. The present analysis shows that sideband contamination to the baseband can be avoided by decreasing the width of pulse elements Δt, i.e. applying oversampling of the pulses. One can define a new parameter characterizing the level of pulse oversampling, as $L_{over} = N_{tot}/R$., where N_{tot} is the total number of pulse elements, $R = b_w T_p$ and $b_w = B_\omega/2\pi$ is the excitation bandwidth in Hz. The contamination is negligible (i.e. $F^*_{RFgap} = F_{RF}$) for $L_{over} \geq 16$ and then the baseband and sidebands profiles become flat with amplitudes equal to $A_k = sinc(k\pi d_c)$.

An approximate expression for the flip angle is $\theta \approx \omega_{1\max}\beta^{-1/2n} d_c\sqrt{T_p/b_w}$ where the $\beta^{-1/2n}$ represents the shape factor, which is related to relative power as $\beta^{-1/n} \approx P(n)$. This approximation holds up to 90° flip angles with an accuracy of about 3%. Unlike conventional pulse (e.g. square, sinc etc.), the same flip angle can be achieved by using a different peak power of HSn pulses. The ratio of peak powers between a square pulse and an HSn pulse is $\omega_{1\max}^{square}/\omega_{1\max}^{HSn} \approx 3\beta^{-1/2n}\sqrt{R}$ which can reach significant values (~60), depending on the R value. The RF energy deposition during an optimized (to "Ernst condition") SWIFT sequence was estimated as $J_{Hsn} \approx 2T_R b_w/(T_1 d_c)$, where T_R is repetition time and T_1 is longitudinal relaxation time. Thus, the energy and SAR of a gapped HSn pulse is independent of pulse length, R value and the specific pulse shape (β and n) and linearly proportional to pulse baseband width. The SAR is less for HSn pulses than for square pulse for high duty cycle and exceeds it if $d_c < 0.33$.





EXPERIMENT AND DISCUSSION Figure 1 presents the shaped pulse with gaps for acquisition in the SWIFT sequence (a) and detailed structure of the pulse with different pulse oversampling levels, L_{over}=1 (b) and L_{over} = 6 (c). In both examples the duty cycle is equal to 0.5.

An example of the effects of pulse imperfections on human head images are shown in Figure 2. The difference in these images reflects only the level of pulse oversampling, which is L_{over} = 1 (bottom images) and L_{over} = 32 (upper images), respectively. After acquiring a set of frequency encoded projections, 3D images are reconstructed using gridding [4] and selected orthogonal slices are presented without any filtering and any corrections. Other acquisition parameters: diameter of FOV= 40cm, b_w = 31kHz, τ_p = 16μs, $\theta \approx 10°$, 256 complex points in radial direction, the total number of spokes (views) 32000 (including positive and negative gradient direction), total acquisition time 4.5min. The bottom images show noticeable "bullseye" artifact, which is almost invisible in upper images, obtained using the oversampled pulse.

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