Application of a Constant Pulse Width VERSE Design to a Silver-Hoult Inversion Recovery Pulse for T1Flair

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Introduction: The RF power deposited (SAR) at high fields scales roughly as the square of the B_0 field and is of increasing concern in clinical practice. Constant amplitude RF pulses are the most power efficient waveforms in terms of achieving a given nutation in a given amount of time. However, when applied with a constant slice-select gradient, they produce very poor slice profiles. A more power efficient means of slice-selective excitation, termed VERSE [1], modulates the slice select gradient waveform and transmit frequency while keeping the RF amplitude as constant as possible (given the limitations of the gradient subsystem).

One desirable feature while scaling the original waveform is preserving its pulse width. This helps maintain sequence timing and consequently contrast. In this work, we describe an algorithm which performs the scaling of the waveforms while maintaining pulse width constant. The new algorithm is applied to reshaping a Silver-Hoult (S-H) inversion recovery (IR) pulse used in conjunction with a fast spin-echo sequence to give considerable improvement in performance.

Methods: We model the variable rate gradient curve to be the Fermi function:

$$F_i(x) = \frac{1}{1+\exp[(|x|-1)/tc]} \qquad (1)$$

where $|x|<=1$ and tc is the time constant. Consider the gradient flat-top of the slice select pulse to be of length N and normalized amplitude 1. The variable-rate gradient can then be written as $G=(A-B).F_n + B$, where B the maximum gradient value needs to be determined, A is the normalized minimum gradient (fixed) and F_n is the normalized Fermi function stretched to fit the interval [0 1]. It can be shown that to preserve gradient area, the following two equations need to be fulfilled :

$$f = 2\cdot tc^2\cdot\ln(2r) - 2\cdot tc\cdot(1-r) - K = 0$$
$$\frac{df}{dr} = \frac{4tc^2}{r} + 2\cdot tc - \frac{4\cdot tc^3}{r\cdot(1-r)}\cdot\ln(2r) \qquad (2)$$

In the above equations, $K=(1-A)/(N\times slew)$ and $r=F_i(0)$. Equation (2) has a solution only if the slew rate exceeds a threshold value. If we limit tc to 1, the minimum slew rate needed (per sampled point on the gradient curve) for a solution is $(1-A)/(0.2219\times N)$. The value of r is determined using the Newton-Raphson method. We start with some initial value of tc (and therefore r) and calculate $\varepsilon_r = -f/(df/dr)$. Once r converges, the values for tc and $B = N\times slew\times tc\times(2r-1)+A$ can be determined. If B exceeds the maximum allowed gradient, B is set to G_{max}. In this case,

$$f = 1-2\cdot tc\cdot\ln(2r) - K_2\cdot tc\cdot(2r-1)^2 = 0, \text{ where } K_2 = N\times slew\times(G_{\max}-1)/(G_{\max}-A)^2 \qquad (3)$$

and we use the maximum slew rate available.

We applied the algorithm to the S-H IR pulse. The waveform scaling factor was tailored so as to achieve good inversion at resonance as well as off-resonance frequencies (at 450Hz corresponding to fat at 3T) keeping in mind constraints related to maintaining adiabatic state throughout inversion [2].

Volunteers were scanned with different coils and protocols on a GE 3T *Excite* scanner equipped with a *TwinSpeed* gradient module (max. amplitude and slew rate of 4G/cm and 150T/m/s). The chosen implementation was for the T1-Flair sequence since typically the IR pulse plays a predominant role in the SAR deposited per unit time for this sequence. Two examples in particular are shown here. In the head, an 8 channel head coil was used to obtain a T1-Flair image (TR=2000ms, TE=17ms, TI=960ms, ETL=6, Slice:4mm/1mm, 27 slices). T1-Flair images of the pelvis (TR=2600ms, TE=Min. full, TI=960ms, ETL=6, Slice:6mm/1mm, 10 slices) were also acquired using a TORSOPA coil. In both studies, the baseline (standard) sequence (labelled sequence 1 here), sequence with only slice select (90°) and slice refocusing VERSE pulses (sequence 2) and the current implementation with VERSE IR, VERSE 90° and VERSE refocusing pulses (sequence 3) were employed.

Results: Comparison images obtained with the standard T1flair sequence (Figures 1(a) and 2(a)) and those with our modified VERSE T1flair sequence (Figures 1(b) and 2(b)) are shown below. The table below shows the reduction in SAR as measured by an external power monitor for the case when the slice coverage is the same for the three sequences. Using the modified S-H IR pulses leads to added reduction in SAR deposition over and above that provided by merely variable-rate gradients for the slice-select and refocusing pulses. Alternately, slice coverage (number of slices per acquisition) can be increased for protocols where the minimum repetition time (TR) is limited by SAR. The slice coverage increases by about 28% for the above head protocol and by about 40% for the given pelvic imaging study.

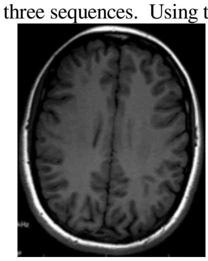

Figure2(a) Standard

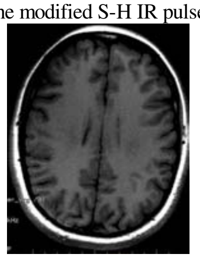

Figure1(b): VERSE

Figure 2(a): Standard

Figure 2(b): VERSE IR-90-180

	SAR REDUCTION			COVERAGE		
	SEQ. 1	SEQ. 2	SEQ. 3	SEQ. 1	SEQ. 2	SEQ. 3
Head	0%	23%	46%	18	21	23
Pelvis	0%	17%	50%	15	18	21

Discussion: Clinical application of SAR intensive pulse sequences, especially ones utilizing relatively high RF power pulses such as the Silver-Hoult inversion recovery pulse, can be severely limited due to FDA approved guidelines for maximum power deposition per unit time. Typically, this can limit scan coverage, increase scan time and require "cool off" periods in practice. Considerable improvement in through-put and scan coverage can then be obtained by using modified VERSE S-H IR pulses in conjunction with VERSE slice select excitation and refocusing pulses. Our VERSE implementation maintains constant pulse width while fulfilling all system constraints.

References: [1] S. Conolly, D. Nishimura, A. Macovski, G. Glover. *J Magn Reson* 1988; 78:440-458.

[2] M. Bernstein, K. F. King, X. Zhou. *Handbook of MRI Pulse Sequences*., Elsevier Academic Press, 2004, 189-200.

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