

A VERSE algorithm with additional acoustic noise constraints

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Introduction

At higher static field strengths of 7T and above specific absorption rate (SAR) and acoustic sound pressure level (SPL) pose limitations on the pulse sequence design. To overcome SAR limitations, the VERSE principle can be used [1]. Here, the envelope of existing rf pulses are modified together with the shape of the slice-selection gradient to selectively reduce high B1 amplitudes during the (often central) portions of the rf pulse. With VERSE, a gradient amplitude modulation is introduced, that can cause additional noise in the pulse sequence. In this work a general VERSE algorithm is presented, that reduces both the B1 amplitude (and thus SAR) and the acoustic noise of the gradient for arbitrary RF pulses. The method is demonstrated for SINC rf pulses.

Methods

In VERSE the amplitude (B_1) of an arbitrary, discretized RF pulse with gradient G is scaled by a function $\alpha(k)$ for each sampling point k to selectively reduce B_1 during peak excitation:

$$\begin{bmatrix} B_1^V(k) \\ G^V(k) \end{bmatrix} t(k) = \begin{bmatrix} B_1(k) \\ G \end{bmatrix} \Delta T, \text{ with } B_1^V(k) = \alpha(k)B_1(k); \quad G^V(k) = \alpha(k)G; \quad t(k) = \frac{\Delta T}{\alpha(k)}.$$

As a consequence, also the dwell time ΔT is adjusted to maintain the RF profile. To include gradient noise optimization the following modified version of VERSE was developed and optimized for SINC pulses:

1. G is increased by a factor $\alpha > 1$ for all sampling points to a predefined maximum value G_{max} . Accordingly, the RF amplitude B_1 is increased by α and the pulse duration T and dwell time ΔT are reduced by $1/\alpha$.
2. The dwell time $t(k)$ of the RF pulse is increased for those samples, where B_1^V (after step 1) is higher than a certain fraction f_{amp} of the maximal amplitude $B_{1,max}$ of the original rf pulse:

$$B_{1,max}^V = f_{amp} B_{1,max}$$

3. The slew rate of the gradient, which is likely above specification limits after step 2, is reduced to a predefined threshold value given in the protocol, here 150 T/m/s.
4. Data points of the RF/gradient pulse are resampled with equidistant dwell time ΔT of the original pulse using a cubic spline function for interpolation.
5. As the acoustic response of the gradient system is known, in the last step the acoustic spectrum of the new slice selection gradient is computed: $g^V(f) = FT(G^V(t))$. For typical rf pulses $g^V(f)$ shows minima at equidistant frequencies; the frequency distance Δf_{min} from the gradient's main resonance frequency to the nearest higher frequency minimum is calculated.
6. In numerical experiments we could show that the cutoff amplitude factor f_{amp} is approximately linear to Δf_{min} over a wide range. Therefore, in a second iteration, the VERSE algorithm is applied again to the rf pulse, but now with a slightly different factor f_{amp} to avoid the acoustic resonance frequencies.

The algorithm was tested on a SINC RF pulses with 256 samples, duration = 2.56 ms, BW = 2 kHz. For the VERSE algorithm, a maximum gradient amplitude of 25 mT/m and a maximum slew rate of 150 mT/m were used. The SPL generated by the gradients of the original SINC pulse and the VERSEd pulse with and without noise optimization were measured on a 7T whole body system (Magnetom 7T; Siemens Medical Solutions; Germany) using a calibrated optical microphone (MO2000, Sennheiser electronic; Germany). At this system, the y-gradient coil has an acoustic resonance of 740 Hz.

Results

Figure 1 shows the rf pulse shape and the respective gradient shape for the original SINC RF pulse and the VERSEd pulses with $f_{amp} = 0.5$ and 0.32 . The duration of the VERSE pulses increases with decreasing amplitude reduction factor. Figure 2 displays the calculated Fourier spectrum of all the three gradient pulses with the respective RF bandwidth of 2 kHz. As $g(f)$ is pronounced at the gradient resonance frequency of 740 Hz for $f_{amp} = 0.5$, an increased SPL of 98.6 dB is measured compared to the SPL of 82.1 dB for the original SINC excitation. After optimization of the rf pulse to the resonance frequency the VERSE pulse with $f_{amp} = 0.32$ generates 85.1 dB, thus 13 dB less than the non-optimized VERSE pulse (cf. Table 1). In a separate experiment it could be shown that the reduction factor has a negligible effect on the slice profile (cp. Fig. 3).

Discussion

In this work a modified VERSE algorithm is presented, which simultaneously optimizes SAR and SPL of an RF pulse. Here the RF amplitude reduction factor f_{amp} was used to modify the acoustic spectrum of the SL gradient, taking into account the known resonance frequencies of the gradient coil. It could be shown that the SPL of the noise optimized VERSE SL gradient could be reduced by up to 13 dB compared to the non optimized VERSE gradient whereas the SAR reduction amounts to a factor of 0.45 compared to the SINC puls. A further reduction of f_{amp} is possible, the next minimum would be at $f_{amp} = 0.18$.

In this implementation the algorithm finds the next higher minimum of $g(f)$ (cp. Fig. 3) to the respective resonance frequency. As an alternative to the amplitude factor f_{amp} , the RF bandwidth can be used as the optimization parameter. In general the optimal RF pulse always is a compromise between sound pressure, RF duration and SAR reduction.

References: [1] Conolly et al. [1988] J Magn Reson 78:440-458.; [2] Hedeem RA and Edelstein WA [1997] Magn Reson Med 37:7-10.

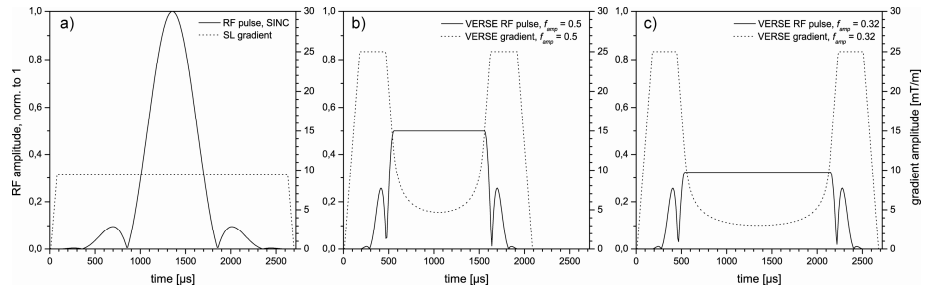


Fig 1: rf pulse shape (solid line) and the respective SL gradient shape (dotted). **a)** standard, Hanning filtered SINC pulse with BW=2kHz.; **b+c)** rf/gradient pulse shapes from a) after VERSE modification with $f_{amp}=0.5/0.32$.

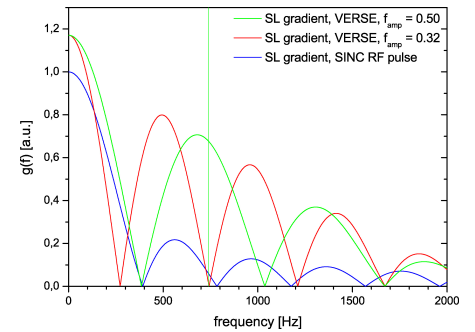


Fig 2: Fourier transforms $g(f)$ of the SL gradients. $g(0)$ of the SINC pulse was set to 1.

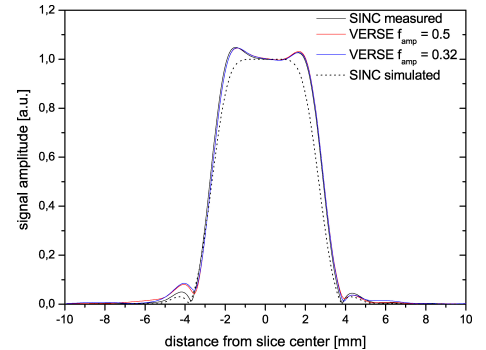


Fig 3: measured profile of a 5mm thick slice, excited with SINC and VERSEd rf pulse. Dotted line: simulated slice profile of a Hanning filtered RF pulse

Pulse	SINC	VERSE $f_{amp}=0.5$	VERSE $f_{amp}=0.32$
Duration [ms]	2.56	1.75	2.31
SAR	1.0	0.67	0.45
SPL [dB]	82.1	98.6	85.1

Tab.1: measured SAR and SPL values of the considered rf- and gradient pulses