Time-Optimal VERSE for Multidimensional and Parallel Excitation

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INTRODUCTION: Variable-rate selective excitation (VERSE) is a RF pulse reshaping technique (1-3). It is commonly used to reduce the peak magnitude and SAR of a RF pulse by reshaping RF and gradient waveforms to reduce RF magnitude while preserving the excitation profile. A general time-optimal VERSE algorithm for multidimensional and parallel excitation pulses is presented. This method is different from other VERSE techniques in that it provides a non-iterative time-optimal multidimensional solution, which drastically simplifies VERSE designs. Compared to other parallel excitation SAR-reduction strategies (4-8), the algorithm is trajectory-independent and allows the user to design pulses without enforcing RF constraints or making excitation error tradeoffs, and to subsequently obtain the shortest pulses possible that satisfy RF and gradient limits.

THEORY: RF pulses and the resultant excitation profiles can be described completely as a function of the Euclidean arc-length in *k*-space, or the so-called "*s*-domain" (9) as defined by Eq. [1]. It can be shown that the spin rotation in this domain is preserved as long as the RF-to-gradient ratio $W(s)$, defined in Eq. [2], is unchanged when VERSE is applied. This relationship also holds for parallel excitation if the RF magnitudes of all channels are scaled by the same value. The key point in our proposed method is to recognize that the peak-RF limit can be translated into a gradient amplitude limit through $W(s)$ in Eq. [2]; thus, reducing the time-optimal VERSE design problem to a time-optimal gradient design. The time-optimal VERSE can be divided into the following three steps: (i) translation of the RF magnitude constraints into gradient magnitude constraints $G_u(s)$ in the *s*-domain as in Eq. [2], (ii) designing a time-optimal gradient $\mathbf{G}^v(s)$ that satisfies the constraints using method introduced in Ref. (10), (iii) modification of the RF magnitude, $B_1^v(s) = W(s)|\mathbf{G}^v(s)|$. ***Parallel Excitation*** Peak RF constraints in parallel excitation can be incorporated via a global gradient upper bound, which is the minimum among upper bounds across all channels. Redesigning RF for *n*th coil from $B_1^n(s)$, $W^n(s)$, and global $G_u(s)$ is the same as in the single channel case. Unlike the local regularization method in Ref. (11), this method sets an exact bound on RF without increasing computational complexity. Note that VERSE'd gradient waveforms can be further used to redesign RF without peak-RF constraint due to its improved realizability. ***SAR Reduction*** It is possible to find a minimum-peak RF solution for a desired pulse length using bisection search on the peak-RF value since the time-optimal pulse length is a non-increasing function of the peak RF; higher peak RF results in shorter or equal RF pulse duration. The resultant pulse, which is bounded in RF and tightly compressed in time, is very efficient in terms of the level of SAR for a fixed pulse-duration.

$$\text{pre}-\text{VERSE}: \{B_1(t), \mathbf{G}(t)\}, \quad \text{post}-\text{VERSE}: \{B_1^v(t), \mathbf{G}^v(t)\}$$

$$s(t) \equiv \gamma \int_0^t |\mathbf{G}(\tau)| d\tau, \quad B_1(s(t)) = B_1(t), \quad \mathbf{G}(s(t)) = \mathbf{G}(t) \qquad [1]$$

$$|\mathbf{G}^v(s)| \le \min\left\{ \frac{B_{1,\max}}{|W(s)|}, G_{\max} \right\} \equiv G_u(s), \quad |\dot{\mathbf{G}}^v(s)| \le S_{\max}, \quad W(s) \equiv \frac{B_1(s)}{|\mathbf{G}(s)|} \qquad [2]$$

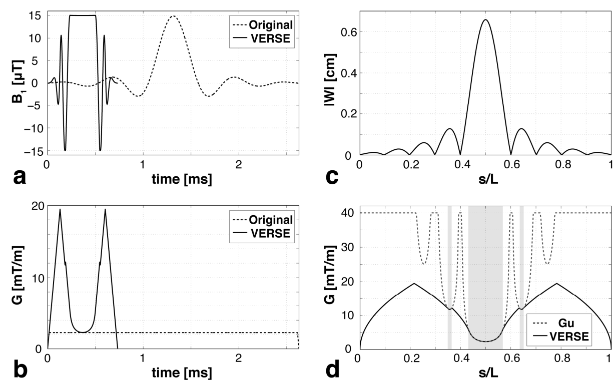

Figure 1. Slab-selective excitation: (a) RF waveforms (b) gradient waveforms (c) RF-to-gradient ratio, $|W(s)|$ (d) gradient upper bound vs. resultant gradient. Horizontal axes are normalized to the total arc-length $L = 2.49$ cm^{-1} in (c,d).

EXAMPLES: Hardware constraints of G_{max} = 40 mT/m, S_{max} = 150 T/m/s, and $B_{1,max}$ = 15 μT were assumed in all our designs, except in the parallel excitation example. All pulses' profiles were verified with Bloch simulation before and after applying VERSE. Figure 1 shows a slab-selective pulse (same pulse specification as in Ref. (3); thickness = 40 mm, time-bandwidth product = 10, and flip-angle = 60°) whose duration decreased by 72.2% for the same peak-RF limit using our method. The minimum-peak pulse was also found using bisection on the RF upper bound while maintaining the pulse's duration. This pulse had 2.6 μT peak-RF magnitude and 71% lower SAR. To validate multidimensional and parallel excitation VERSE, we applied our algorithm to an inversion pulse with a 10 cm × 5 cm rectangular target profile (a single-shot spiral-out excitation *k*-space trajectory used; resolution = 0.75 cm, FOV = 24 cm, excitation FOV = 5 cm; speedup factor = 4.8) designed by the additive angle method (12). Without VERSE, the large flip-angle of this pulse combined with a high acceleration factor results in very high peak RF. We set $B_{1,max}$ = 15 (arbitrary units), or approximately 30% of the original peak as shown in Fig. 2d. The resulting time increase was 17%, which is small compared to the 230% time increase by simple uniform time-dilation approach.

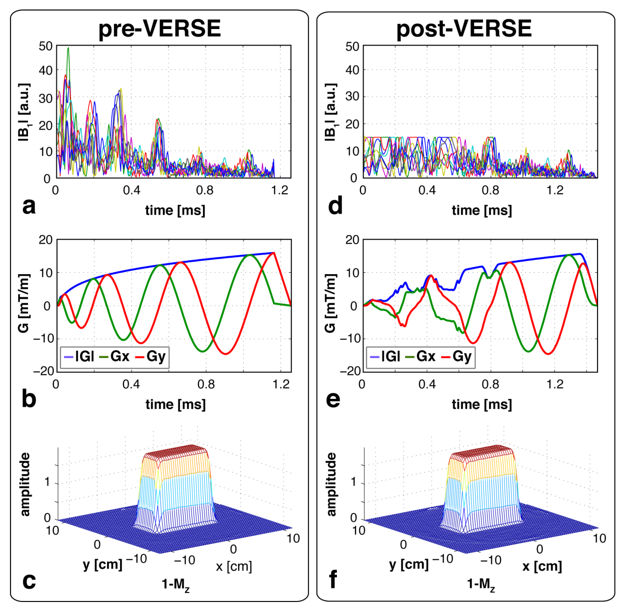

Figure 2. 2D parallel excitation with 8-channel: (a-c) original waveforms (d-f) VERSE'd waveforms. (a,d) RF waveforms (b,e) gradient waveforms (c,f) simulated π excitation profiles.

CONCLUSION: We developed a non-iterative time-optimal design method for VERSE, and validated it with representative examples. Time-optimality was achieved by translating peak-RF limits into gradient upper bounds in excitation *k*-space that are fed into a time-optimal gradient waveform design. A minimum-peak RF solution, found by this method, efficiently reduces SAR of fixed-duration pulses.

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