A General Numerical VERSE RF Pulse Design Framework

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Target Audience: MR physicists and engineers interested in flexible RF pulse design.

Purpose: Time-efficient VERSE[1] pulses are often designed in two-step processes by first designing, then compressing RF and accompanying gradient pulses[2,3]. In other cases, VERSE pulses may be designed according to analytic solutions of differential equations[4]. Motivated by a flexible, numerical spiral trajectory design algorithm[5], we have developed a similar, simple process for RF pulse design. In this work a general, single-step framework is presented for multidimensional VERSE RF pulse design using a numerical approach.

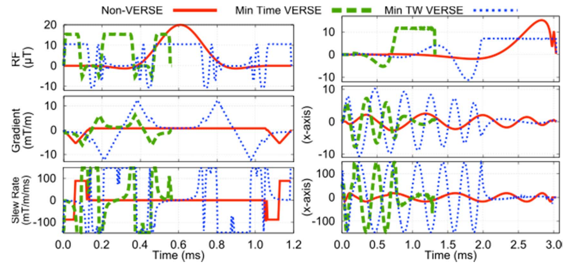

Figure 1: Slab-selective (left) and 2D spiral pulses.

Methods: In the numerical spiral design method, rather than solving a set of differential equations, simple calculations from base analytical equations are performed to see if the next desired point can be reached within gradient amplitude and slew rate limits. If the next desired point is infeasible, the algorithm steps back and recommences with smaller step sizes. A sign array is stored which indicates whether large (sign=1) or small (sign=-1) steps should be taken. By parameterizing the RF signal b_1 as a function of k-space, the numerical approach is applicable to VERSE design by viewing RF pulse design as a trajectory design problem with an additional peak RF constraint. b_1 is proportional to the gradient amplitude, so at each step, the k-space trajectory spacing, $|\boldsymbol{k}_{n+1}-\boldsymbol{k}_n|$, must be reduced until $b_1[n] \leq b_{1,max}$. Determining $\boldsymbol{k}_{n+1}$ from $\boldsymbol{k}_n$ is based on the trajectory corresponding to the RF pulse type. For slab selection, this is a line. For 2D spatial excitation this is, in this case, a spiral. The numerical VERSE procedure is given in the table. For a slab-selective pulse, the flexibility of the design procedure allows a balanced pulse to be designed in which RF is applied during positive and negative portions of the gradient. A 70° flip angle, balanced, slab-selective, Hamming-windowed sinc pulse with 14 cm thickness, and a 90° flip angle 2D spiral spatially selective pulse with 20 cm field of view (FOV), and 14 cm circular field of excitation intended for outer volume suppression[4] were tested with the proposed method. For each pulse type, two VERSE pulses were designed while maintaining the energy of the non-VERSE pulse. First, a minimum duration pulse, and second, a pulse with minimal transition width (Min-TW) keeping the duration of the non-VERSE pulse. Scans were run on a 1.5 T GE Signa Excite scanner. Slab-selective pulses were used for excitation in a 3D Cartesian sequence with a 30×12×12 cm³ FOV and 1×2×2 mm³ resolution. The 2D spiral pulses were used for excitation in a 2D Cartesian sequence with a 40×40 cm² FOV and 2 mm resolution.

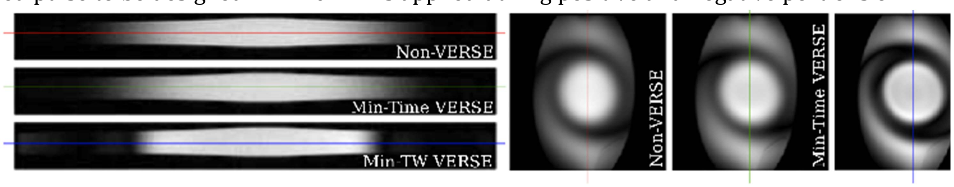

Figure 2: Slab selective (left) and 2D spiral pulse images (right) using non-VERSE, Min-T VERSE, and Min-TW VERSE designs.

Initialize sign[n]=1 for all n.
For nth point in k-space, $\boldsymbol{k}_n$, with gradient $\boldsymbol{g}_n$, and sampling period Δt,
1. Determine direction of trajectory based on RF type $\boldsymbol{u}$.
2. Find the gradient constrained range $\mathbf{K}_g = \{\boldsymbol{k} : |\boldsymbol{k}_{n+1}-\boldsymbol{k}_n| < G_{max}\Delta t\, \gamma/2\pi\}$
3. Find the slew rate constrained range $\mathbf{K}_s=\{\boldsymbol{k} : |(\boldsymbol{k}_{n+1}-\boldsymbol{k}_n)2\pi/(\Delta t\, \gamma)-\boldsymbol{g}_n| < S_{max}\Delta t\}$
4. Find intersection of the ranges $\mathbf{K}_n = \mathbf{K}_g \cap \mathbf{K}_s \cap \boldsymbol{k}_n + a\boldsymbol{u}$ where $a \in \mathbb{R}$
5. If sign[n]=1, $\boldsymbol{k}_{n+1} \in \mathbf{K}_n$ maximizing $|\boldsymbol{k}_{n+1}-\boldsymbol{k}_n|$ subject to $b_1(\boldsymbol{k}_{n+1}) \leq b_{1,max}$
6. If sign[n]=-1, $\boldsymbol{k}_{n+1} \in \mathbf{K}_n$ minimizing $|\boldsymbol{k}_{n+1}-\boldsymbol{k}_n|$ subject to $b_1(\boldsymbol{k}_{n+1}) \leq b_{1,max}$
7. If $\boldsymbol{k}_{n+1}$ does not exist, step back until sign[n+1]=1 then set sign[n+1]=-1

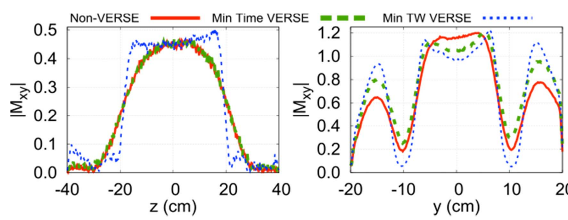

Figure 3: Slice profile cross sections of slab selective (left) and 2D spiral (right) excitations.

Results/Discussion: The Min-Time VERSE design reduced the RF pulse durations from 1.19 to 0.57 ms and 3.04 to 1.32 ms for the slab-selective and 2D spiral pulses, respectively. Similarly, the Min-TW VERSE design reduced transition width by 73% and 45%, respectively. In the acquired images shown in Fig. 2, with corresponding cross sections in Fig. 3, it can be seen that the Min-Time pulses maintain the slab profile and the Min-TW pulses exhibit sharper cutoffs.

Conclusions: It has been shown that a simple, single-step framework can be used to design various VERSE RF pulses. Future work includes designing additional RF pulse types and testing the designs at higher main field strengths where specific absorption rates are a stricter limiting factor.

References: [1] Conolly S, et al. JMR 1998; 78(3):440-458. [2] Hargreaves B, et al. MRM 2004; 52:590-597. [3] Lee D, et al. MRM 2009; 61(6): 1471–1479. [4] Xu D, et al. MRM 2007; 58:835–842. [5] Pipe J, et al. MRM 2013. [6] Smith T, et al. MRM 2012; 67:1316–1323.