VERSE-Guided Numerical RF Pulse Design

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INTRODUCTION

Numerical optimization-based RF pulse design methods are widely used to incorporate system non-idealities and non-linearities such as field inhomogeneities, coil sensitivities, and signal decay [1-3]. These approaches often lead to RF pulses with high peak RF magnitude exceeding the hardware or safety limits and the variable-rate selective excitation (VERSE) principle can be utilized to directly constrain the peak RF power on-the-fly [4-7]. However, discrete-time implementations of VERSE may not preserve spins' rotational behavior due to the imperfect system modeling and sampling. Also, the excitation profile of reshaped pulses is affected by time-dependencies (e.g. off-resonance, T_2 relaxation) that are not accounted for in VERSE. To effectively correct these errors while achieving a fast peak RF power control, VERSE-guided numerical RF pulse design framework is introduced for parallel transmit applications.

THEORY

According to the VERSE principle, spins' rotational behavior during an RF pulse is preserved by maintaining the ratio of RF magnitude to gradient amplitude, W(s), in excitation *k*-space [7]. Hence, peak RF power can be controlled alternatively by gradient amplitude manipulation. Previously, this continuous-time VERSE (ct-VERSE) was applied to discrete-time waveforms, based on the assumption that the interpolated waveforms do not incur noticeable distortions [7]; henceforth this is denoted as discrete-time VERSE (dt-VERSE).

***dt-VERSE*:** As summarized in Fig. 1, a discrete-time pre-VERSE pair $\{B_1[n],\mathbf{G}[n]\}$, is first converted to a continuous-time waveform pair $\{B_1(t),\mathbf{G}(t)\}$, according to the system responses of RF/gradient hardware; this determines the excitation pattern and W(s) is calculated from this continuous-time pre-VERSE pair. Once the gradient waveforms are reshaped to $\mathbf{G}^v(t)$, the reshaped RF waveform, $B_1^v(t)$, is determined by the ct-VERSE process. Finally, the resultant waveforms are sampled for scanner use, yielding $\{B_1^v[n],\mathbf{G}^v[n]\}$. Note that the true RF-to-gradient ratio, $W^d(s)$, is found by applying true system responses to $\{B_1^v[n],\mathbf{G}^v[n]\}$, whose deviation from W(s) indicates the inherent error introduced through dt-VERSE process. In practice, imperfect system modeling introduces error even in W(s) that contributes to the distortions in the excitation profile.

***reVERSE*:** Shifting our focus from perfect system modeling, here we propose "RF redesign after VERSE", termed reVERSE, as an alternative method; it reapplies the original RF pulse design routine on the post-VERSE gradient waveforms. In this way, we not only mitigate the inherent error of dt-VERSE but also take the time-dependent effects such as off-resonance into account.

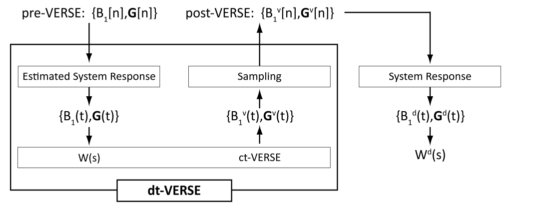

Figure 1. dt-VERSE utilizes ct-VERSE assuming that interpolation on discrete-time waveforms would not incur noticeable distortions. The true RF-to-gradient ratio, $W^d(s)$, is found by applying the true system response to the result of dt-VERSE, whose deviation from W(s) indicates the inherent error in dt-VERSE process.

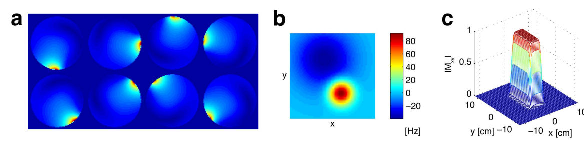

Figure 2. Simulation setup for 2D spatial excitation. (a) $|B_1^+|$: Magnitude of transmit sensitivity patterns of eight-channel parallel excitation. (b) B_0: off-resonance field map. (c) Desired excitation profile: 5 cm × 10 cm rectangle blurred via convolution with a Gaussian kernel of FWHM = 1.2 cm.

EXAMPLE

Accelerated 2-D spatial excitation RF pulses for 8 channel transmit coils were designed with echo-planar (EP) excitation *k*-space trajectories assuming G_{max} = 40 mT/m, S_{max} = 150 T/m/s, and 4 µsec sampling time [8]. All spatial domain information was specified on the same 64 × 64 grid within 24 cm ROI. Modeled ransmit sensitivity patterns ($|B_1^+|$ maps shown in Fig. 2a) for 8 channels [9] and off-resonance field map (B_0 map, Fig. 2b), were fed into RF pulse designs and numerical simulations. Excitation pulses targeted a spatial resolution of 0.75 cm and FOX of 9 cm; a 5 cm × 10 cm rectangular target profile achieving a 90° flip angle was blurred via convolution with a Gaussian kernel of FWHM = 1.2 cm (Fig. 2c). 25 CG iterations were executed at each perturbation pulse design and we stopped the pulse design alternations when the normalized root-mean-square error (NRMSE) between the desired and Bloch-simulated magnetization reached 0.5%. Figure 3 shows simulations of the 2-D spatial excitation example. Original RF waveforms with time-optimal gradient waveforms in echo-planar (EP) trajectory possess very high peak RF (Fig. 3a) and a 25% reduction of peak RF power was the goal of pulse reshaping; the original waveforms are reshaped to the post-VERSE pair in Fig. 3d,e and only the RF waveforms are adjusted by reVERSE (Fig. 3f). The resultant relative NRMSE among pre-, post-VERSE, and reVERSE was 1:21:1; reVERSE successfully recovered the original NRMSE level.

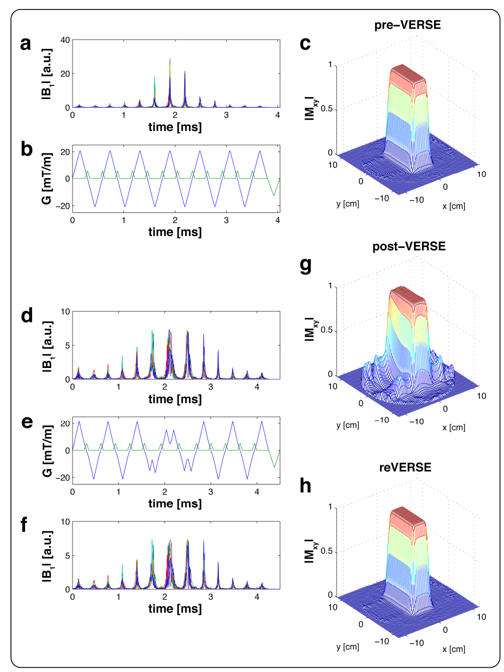

Figure 3. 2D spatial excitation by reVERSE. RF pulses were designed and simulated with 4 µsec sampling time. (a-c) pre-VERSE. (d-h) post-VERSE vs. reVERSE. Excitation patterns are compared for pre-VERSE (c), post-VERSE (g), and reVERSE (h) and corresponding RF waveforms and gradient waveforms are depicted on the left of each excitation pattern. Note that post-VERSE and reVERSE share the same gradient waveform (e).

CONCLUSION

We have introduced a "VERSE-guided numerical RF pulse design" framework as a fast method for peak RF power control that is self-compensated for errors from both discrete-time implementations and time-dependencies in VERSE. This approach is particularly useful when RF pulses need to be numerically designed online to incorporate subject dependent field variations and coil sensitivities in parallel transmit applications.

REFERENCES: [1] Katscher, U et al., *Magn Reson Med,* 2003; 49:144-150 [2] Zhu, Y et al, *Magn Reson Med,* 2004; 51:775-784 [3] Grissom, WA et al., *Magn Reson Med* 2006; 56:620-629 [4] Conolly, S et al., *J Magn Reson* 1988; 78:440-458 [5] Conolly, S et al., *Magn Reson Med* 1991; 18:28-38 [6] Hargreaves, BA et al., *Magn Reson Med* 2004; 52:590-597 [7] Lee, D et al., *Magn Reson Med* 2009; 61:1471-1479 [8] Grissom, WA et al., *IEEE Trans Med Imaging* 2009; 28:1548-1559 [9] Kurpad, KN et al., *ISMRM* 2005, p. 16