Time-Optimal VERSE Excitation for 3D Balanced SSFP Imaging

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Introduction: Balanced steady-state free precession (SSFP) imaging (TrueFISP, FIESTA, balanced-FFE) is a rapid imaging method that provides good tissue contrast with high SNR efficiency. However, maintaining high SNR efficiency requires a high readout duty cycle. This is often achieved by shortening the excitation pulse, which compromises the 3D slab profile. A mediocre slab profile results in fewer useful slices, both because of through-slab aliasing and diminished contrast due to reduced flip angle in the transition band. This is especially true when a thin slab is used to limit the field of view. In this work, we apply variable-rate selective excitation (VERSE) to design short-duration pulses with sharp slab profiles that are appropriate for 3D balanced SSFP imaging.

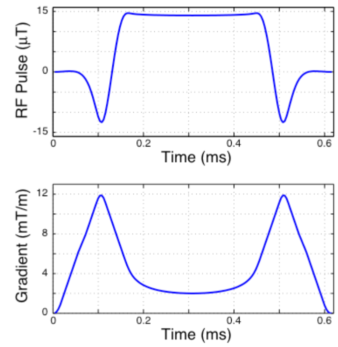

Figure 1. *Minimum-time VERSE RF and gradient pulses for a time·bandwidth (TB) of 5, and a slab width of 4.0 cm.*

Methods: Variable-rate selective excitation (VERSE) pulses can use a time-varying gradient to traverse excitation k-space more slowly in regions of high RF amplitude [1], which can reduce RF power deposition [1,2]. However, VERSE can instead be used to minimize the duration of a selective RF/gradient pair. For minimum-time VERSE, the RF/gradient pair is always limited by maximum RF amplitude, maximum gradient amplitude, or maximum gradient slew rate.

We begin with standard linear-phase RF pulses designed using Shinnar-Le Roux (SLR) pulse design [3]. Each RF pulse is then converted to the time-optimal VERSE RF/gradient pair using a recursive design algorithm [4]. The RF pulse time·bandwidth product (TB) is proportional to the ratio of slab width to transition width. Thus TB is a useful measure of profile sharpness.

Using a steady-state Bloch simulation, we calculated theoretical slab profiles for TB=1.5, TB=5 and TB=10 pulses. These were verified using 3D balanced SSFP sequence with 64 slices, 2mm slice thickness, TR=5ms and a 60° flip angle to image a doped water phantom (T_1/T_2=350/300 ms). The same sequence was used *in vivo* with cardiac-gating and a breath hold to image with 2x2 mm in-plane resolution, 30 sections of thickness of 3 mm, and the TB=10, 40 mm slab-select VERSE RF/gradient pulse pair.

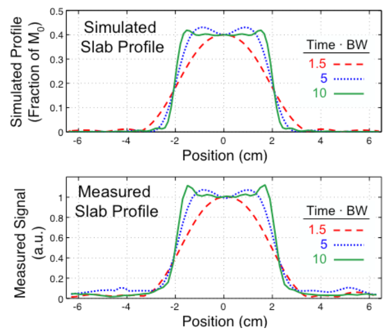

Figure 2. *Excellent agreement is shown between simulated (top) and experimentally measured (bottom) profiles for TB=1.5, 5 and 10 pulses.*

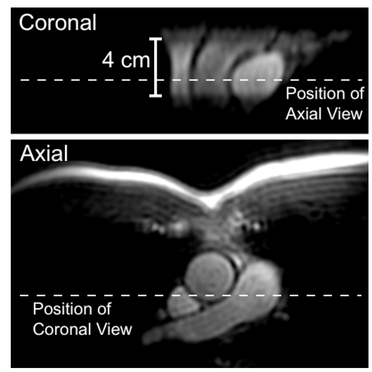

Figure 3. *Coronal (top) and axial (bottom) views from a 3D acquisiton slightly above the heart. Images have 2x2x3 mm resolution. The coronal image shows the 4cm, TB=10 slab profile in vivo. The contrast is consistent across the slab, indicating a flat slab profile. The black level is 0 for these images.*

Results: Figure 1 shows a sample VERSE RF/gradient combination for TB=5. (The original RF pulse is very similar to a "sinc" pulse.) Figure 2 shows the simulated and measured profiles for TB=1.5, TB=5 and TB=10. The simulated and measured profiles show excellent agreement. Figure 3 shows that the *in vivo* slab profile matches both the simulated profile and the phantom profile well. Thus the through-slab field-of-view could be reduced without aliasing. Note the consistent contrast throughout the slab.

Discussion: VERSE pulses allow significant improvements in slab profile with only a small increase in pulse duration, as shown in Figure 4. Although the RF power deposition increases with TB (or sharpness), Fig. 4 indicates that SAR limits are met. Since most of the energy of the VERSE pulses is still in the central lobe, SAR could be decreased with a small increase in pulse duration. Compared with standard selective excitation pulses, VERSE pulses are more sensitive to resonant shifts and RF/gradient timing. We have found that RF/gradient misalignments of up to ±8 microseconds do not adversely affect the measured profiles. Resonant shifts of up to ±100 Hz result in less than a 10% increase in the background signal; larger shifts are assumed to be not present in balanced SSFP imaging. The use of VERSE slab excitations will be particularly useful in cardiac and abdominal imaging applications [5,6].

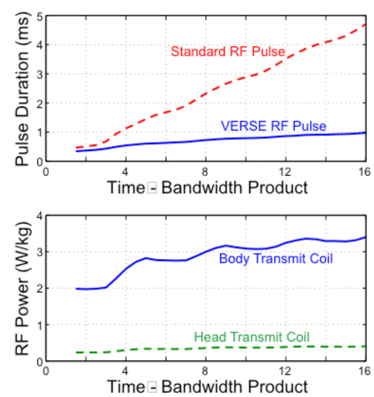

Figure 4. *RF pulse duration (top) and power deposition (bottom) as a function of the RF pulse TB product.*

Conclusion: Minimum-time VERSE RF pulses allow very sharp slice profiles and reasonably short pulse durations. These pulses are particularly useful for 3D balanced SSFP imaging, where moderately high angles are needed across the whole profile to maintain image contrast. While meeting SAR and RF amplitude limits, VERSE pulses allow a factor of 3 to 4 reduction in duration to less than 1 ms for a very sharp slab profile.

References:

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