Variable-Rate Selective Excitation for Rapid MRI Sequences

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Balanced steady-state free precession (SSFP) imaging sequences require short repetition times (TRs) to avoid off-resonance artifacts. The use of slab-selective excitations is common, as this can improve imaging speed by limiting the field of view (FOV). However, the necessarily short-duration excitations have poor slab profiles. This results in unusable slices at the slab edge due to significant flip-angle variations or aliasing in the slab direction. Variable-rate selective excitation (VERSE) is a technique by which a time-varying gradient waveform is combined with a modified RF waveform to provide the same excitation profile with different RF power and duration characteristics. With the use of VERSE, it is possible to design short-duration pulses with dramatically improved slab profiles. These pulses achieve high flip angles with only minor off-resonance sensitivity, while meeting SAR limits at 1.5 T. The improved slab profiles will enable more rapid 3D imaging of limited volumes, with more consistent image contrast across the excited slab. Magn Reson Med 52:590–597, 2004. © 2004 Wiley-Liss, Inc.

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Recent improvements in gradient hardware have enabled the clinical use of very rapid MRI sequences, especially balanced steady-state free precession (SSFP) imaging (1,2), also known as TrueFISP, FIESTA, or balanced-FFE. Balanced SSFP imaging provides a high signal-to-noise ratio (SNR), as much as 1.5 times that of gradient-spoiled sequences. Additionally, the combination of good tissue contrast and short repetition times (TRs) makes it a good sequence for 3D clinical imaging with low scan times. An excellent description of balanced SSFP imaging was given by Scheffler and Lehnhardt (3).

When balanced SSFP is used, frequency variations due to static field or susceptibility that are beyond a certain range result in significant signal loss (4, 5). This sensitivity to field variations is reduced by the use of a very short TR (typically 3–5 ms), although even shorter TRs are being explored, as described, for example, in Refs. 6 and 7. The short TR places a significant limitation on the achievable image resolution when standard gradients are used. In addition, as TR is decreased, the fraction of time used for data acquisition decreases. Ultimately this can result in a loss of SNR efficiency to the point where the advantages of balanced SSFP compared to gradient-spoiled or RF-spoiled sequences are lost.

The time available for imaging is limited by the need to keep TR short, as well as by the duration of the excitation pulse. Thus the excitation pulse usually has a rough profile, or is nonselective. However, in many 3D imaging applications, it is desirable to use a slab-selective excitation pulse to allow reduction of the imaging field of view (FOV), which decreases scan time. Furthermore, a flat slab profile is important, as flip-angle variations lead to inconsistent contrast across slices. The requirements of a flat profile and a sharp transition to limit FOV would normally require a long-duration excitation pulse.

Variable-rate selective excitation (VERSE) is a technique that uses a time-varying gradient to change the shape of the radiofrequency (RF) pulse without changing the spatial excitation profile on resonance (8–10). VERSE excitation pulses have been primarily applied to RF power reduction (8,10–12). Similar approaches have been used for adiabatic inversion pulses to minimize shifts due to resonant offsets (13–16).

The original description of VERSE (8) also included a method for minimum-time VERSE pulse design. In this work, we used a numerical technique to include gradient slew rate limits in the VERSE method. We designed short-duration pulses with slab profiles that were significantly sharper than those typically used in balanced SSFP imaging. After we validated these pulses in phantom tests and in vivo imaging, we explored the sensitivity of reduced-time VERSE pulses to timing and off-resonance, as well as the relationship between slab sharpness, RF power, and pulse duration.

THEORY

We can describe the design of selective excitation pulses using a *k*-space formalism (17) that views excitation from a frequency-domain paradigm: the gradient waveform describes a trajectory through excitation *k*-space, while the RF waveform deposits energy at different spatial frequencies. The Shinnar-Le Roux (SLR) pulse design algorithm uses a more accurate mapping between the RF waveform and the excitation profile (18). SLR pulse design is very powerful, as it employs existing digital filter design principles for selective RF pulse design. For example, with the use of SLR pulse design, it is possible to design the optimal equi-ripple profile for a given time $\times$ bandwidth product (TB). We use TB throughout this work as a measure of slice profile sharpness, since TB is proportional to the ratio of the slice width (full-width at half-maximum (FWHM)) to the transition width of the profile. Note that although we

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chose to use SLR pulse design, the reduced-time VERSE technique presented below will work with other RF pulse design techniques, such as simulated annealing (19) or varying phase approaches (20).

VERSE

Variable-rate selective excitation (VERSE) pulses can use a time-varying gradient to traverse excitation *k*-space at different rates. The primary application of VERSE has been to reduce the gradient waveform in regions of high RF amplitude, which in turn reduces RF energy (8,11,12). In this work, our goal was to use VERSE to instead minimize the duration of excitation pulses by *increasing* both RF and gradient amplitudes as much as practical limits would allow. In this section we review the continuous time VERSE principle (9,10), and then pose the minimum-time VERSE problem in the next section.

A "standard" RF pulse, *b(t),* is played with a constant selection gradient of amplitude *g.* To achieve the same excitation profile, a VERSE RF pulse $b_\upsilon(t)$ and the corresponding time-varying gradient $g_\upsilon(t)$ can be defined as follows:

$$b_\upsilon(t) = b(\tau(t))\dot{\tau}(t) \qquad [1]$$

$$g_\upsilon(t) = g\dot{\tau}(t), \qquad [2]$$

where $b(t)$ is the original RF waveform, g is the amplitude of the constant gradient waveform, and $b_\upsilon(t)$ and $g_\upsilon(t)$ are the VERSE RF and gradient waveforms respectively.

The standard (constant-gradient) RF waveform is defined for $t \in [0, T]$, while the VERSE RF and gradient waveforms are defined for $t \in [0, T_\upsilon]$. The transformation to VERSE pulses is defined by the selection of the "time dilation function," $\tau(t)$, which has the same units of time as *t,* and end-point constraints $\tau(0) = 0$. and $\tau(T_\upsilon) = T$.

Minimum-Time VERSE

The design of minimum-time VERSE pulses requres selection of $\tau(t)$ for $t \in [0, T_\upsilon]$, such that T_υ is minimized under the following constraints:

1. $\tau(t)$ is monotonically increasing from $\tau(0) = 0$ to $\tau(T_\upsilon) = T$.
2. $|b_\upsilon(t)| \leq B_{max}$.
3. $|g_\upsilon(t)| \leq G_{max}$.
4. $\left|\dfrac{dg_\upsilon(t)}{dt}\right| \leq S_{max}$.

where B_{max}, G_{max}, and S_{max} are respectively the maximum RF amplitude, maximum gradient amplitude, and maximum time-rate-of-change of the gradient. It is assumed that the gradient waveform is always non-negative.

An iterative VERSE design technique and approximation for the time-optimal solution was previously employed for the design of 2D pulses (9). However, to our knowledge, there is no known closed-form solution for this selection of $\tau(t)$. In the next section we describe a recursive procedure that numerically evaluates VERSE pulses that closely approximate the above conditions.

MATERIALS AND METHODS

In this section we describe the pulse design procedure used in the current study. We simulate excitation pulses for steady-state sequences, and validate these pulses in phantoms and in vivo images. Finally, we explore the effect of slice profile sharpness on the duration and RF power of the excitation pulses.

Design Procedure

We begin with standard linear-phase RF pulses designed with the use of SLR pulse design (18). We define the RF pulse time $\times$ bandwidth product (TB) as the duration of the standard RF pulse multiplied by the half-maximum bandwidth of the excitation profile. We note that TB is proportional to the ratio of slab width to transition width, and is a useful measure of profile sharpness. In all cases, we design a slab width of 40 mm to represent a narrow, practical slab width, since wider slabs will result in even shorter-duration pulses for a given TB.

Each RF pulse is then converted to the time-optimal VERSE RF/gradient pair by means of a recursive design algorithm, as follows (21,22):

1. The RF waveform is uniformly compressed in time until the maximum RF amplitude is reached.
2. The constant gradient waveform amplitude (g) for the initial RF pulse and given slab thickness is calculated.
3. Ignoring the gradient slew rate limit, the gradient waveform and RF are compressed together in time so that either the RF or the gradient are always at the maximum amplitude.
4. The end-points of the gradient and RF are set to zero.
5. At each point in the gradient where the slew rate is violated, the gradient and RF waveforms are expanded together in time to eliminate the slew-rate violation, while maintaining the same excitation k-space RF deposition. *This step is applied recursively, as expanding one time point often results in a slew violation elsewhere in the waveform.*
6. Both RF and gradient waveforms are resampled with the use of a uniform sampling rate so that the waveforms can be played on a real system.
7. The resulting gradient waveform is low-pass-filtered to a bandwidth of 50 kHz to reduce the likelihood of exceeding gradient amplifier bandwidth, and the RF waveform is correspondingly altered.

The intent of the above algorithm is to achieve a near time-optimal VERSE RF/gradient pulse pair that achieves a given slab profile. As an example of this design process, Fig. 1(a and c) shows the "standard" slab-selective RF/gradient waveforms (with a constant gradient waveform during the RF pulse) corresponding to steps 1 and 2 above. The minimum-time VERSE RF/gradient pair is shown in Fig. 1(b and d). A significant time reduction (from 2.9 ms to 0.8 ms) is obtained by the use of the reduced-time VERSE design. The VERSE excitation is very close to one of the limits (maximum RF or gradient amplitude or maximum gradient slew-rate) for the entire duration of the pulse.

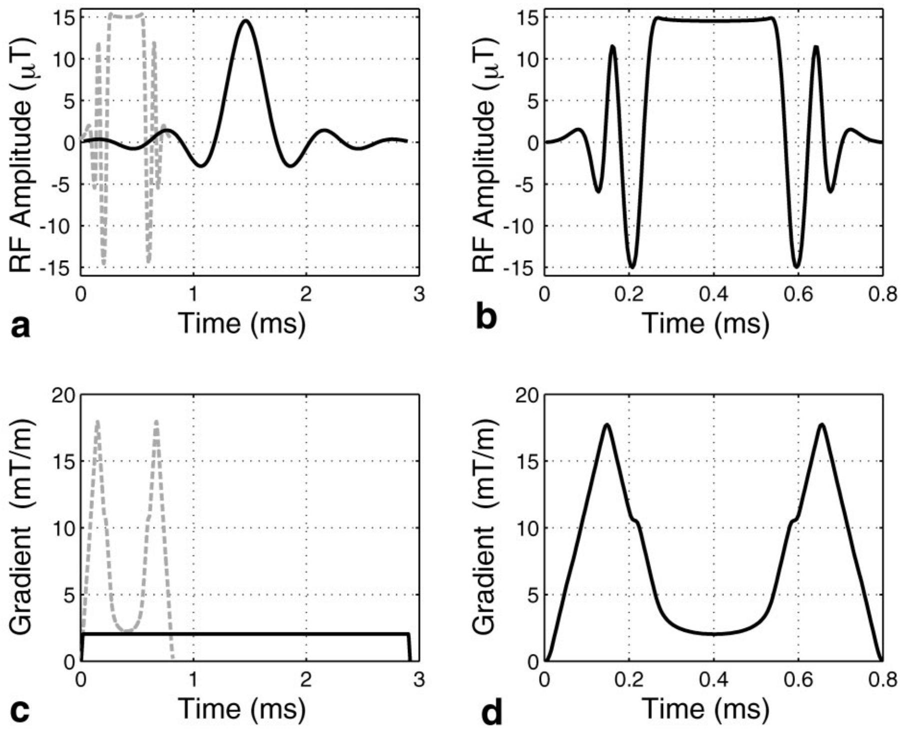

FIG. 1. Standard TB = 10 slab-selective RF (**a**) and gradient (**c**) waveforms (black lines). With the use of an iterative procedure, the minimum-time VERSE RF (**b**) and gradient (**d**) are obtained. (These are also shown as dashed gray lines in **a** and **c**). The use of VERSE leads to a reduction in duration (from 2.9 ms to 0.8 ms), at a cost of increased gradient amplitude and RF energy.

Simulations

As an initial validation, we simulate the slab profiles of all of the reduced-time excitation pulse pairs. As these excitations are intended to be applied to balanced SSFP imaging sequences, the goal is to simulate the *steady-state* excitation profile. We used a Bloch equation simulation that calculates the precession and decay matrices using the RF and gradient waveforms for each of a set of resonant frequency and spatial offsets. At each spatial offset, a resulting matrix equation is solved such that the magnetization is the same from one sequence repetition to the next, as in Refs. 23 and 24. This steady-state Bloch simulation was coded in Matlab 6.5 (The Mathworks, Natick, MA), and is available for general use at http://www-mrsrl.stanford.edu/~brian/blochsim.

For a 40-mm slab thickness, we designed 60°-flip-angle RF pulses with TB = 2, TB = 5 and TB = 10, and used the minimum-time VERSE algorithm to shorten the latter two pulses. The design parameters used were a maximum gradient amplitude of 40 mT/m, a maximum gradient slewrate of 150 T/m/s, and a maximum RF amplitude of 15 μT. Both the RF and gradient waveforms were sampled at 4-μs intervals. The spatial profiles of each pulse pair were generated by means of the steady-state Bloch simulation described above, assuming a sequence TR of 5.0 ms, and all gradients were fully refocused over the sequence repetition. All of the parameters described here apply throughout this work, unless otherwise noted.

Compared with a standard excitation (constant gradient), VERSE pulses will have different sensitivity to resonant frequency offsets, as well as to timing delays between the RF and gradient waveforms. Both of these effects will distort the VERSE profile more than they would distort the profile of a standard waveform. However, due to increased gradient amplitude, the minimum-time VERSE profile may be shifted less due to resonant offsets than that of a standard excitation. In balanced SSFP sequences, there is an implicit assumption that the resonant frequency variation over the volume of interest is small. However, it is useful to examine the effect of off-resonance on the slice profile. We repeated the simulation to generate the steady-state slice profile for the TB = 10 pulse pair using the Bloch simulation at resonant offsets of 0 Hz, 200 Hz, 400 Hz, and 600 Hz. We also repeated the simulation whereby an intentional delay of 0, 4, 8, and 12 μs is applied between the RF waveform and the gradient waveform.

Slice Profile Measurements

We verified the simulations of slice profile using a 3D balanced SSFP sequence with 64 slices, 2-mm slice thickness, TR = 5 ms, and a 60° flip angle. The TB = 2, TB = 5 and TB = 10 excitations were individually tested. The scans were performed with a standard quadrature transmit/receive head coil on a 1.5 T G.E. LX scanner (G.E. Medical Systems, Waukesha, WI) with CV/i gradients (40 mT/m maximum amplitude and 150 T/m/s maximum slew rate). We used a cylindrical phantom of water doped with MnCl, $T_1/T_2 = 350/300$ ms.

As discussed above, the slab profile was designed to be 40 mm. Thus the 64-slice 3D imaging sequence sampled well outside the excited slab. The amplitude for each slice was taken as the sum of pixel magnitudes over the entire slice. A plot of slice amplitude as a function of slice position was made for each of the three excitations.

In Vivo Validation

The same sequence used for phantom validation was combined with cardiac gating and a breath-hold for in vivo

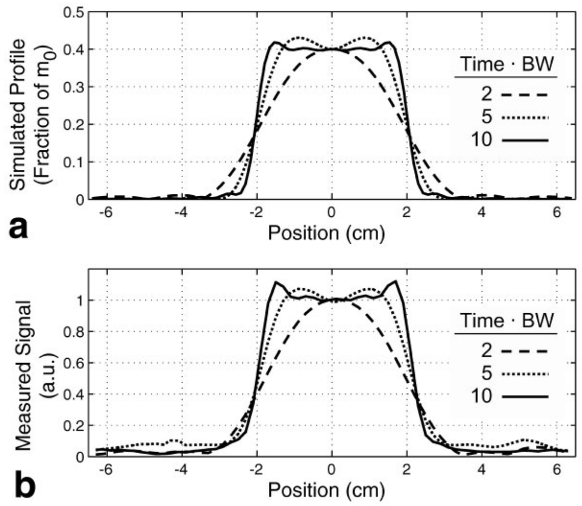

FIG. 2. (**a**) Simulated and (**b**) measured steady-state slab profiles for TB = 2 (dashed line), TB = 5 (dotted line), and TB = 10 (solid line) minimum-time VERSE excitations. There is excellent agreement between the measured and simulated pulse profiles.

validation of the slab profile for the TB = 10 excitation. Other parameters included 2×2 mm in-plane resolution, and 30 sections of 3-mm thickness. The resulting slab-direction FOV of 9 cm was well beyond the width of the slab, so that the slab profile could be studied. An axial slab was selected slightly above the heart, and a breath-hold of 30 heartbeats and a 15 cm surface coil were used for image acquisition. A 3D reconstruction of this image was made for visualization of the slice profile.

Pulse Duration and RF Power Comparisons

We verified a few specific VERSE excitation pulses. However, for general design purposes, it is useful to examine the minimum-time VERSE excitation duration and RF energy as the design parameters are varied. We repeated the design for flip angles of 30°, 60°, and 90°, and TB values between 2 and 20. The same RF and gradient amplitudes listed above were used for this design. The duration of the standard and VERSE excitations, and the RF energy of each VERSE RF waveform were measured for each different case.

Since an imaging scan uses many RF pulses, the RF power deposition in a patient, also called specific absorption rate (SAR), is proportional to the RF energy in each pulse. Compression of excitation pulses in time generally increases RF energy (or RF power deposition in the patient). Thus minimum-time VERSE pulses will result in a relatively high RF energy for a given profile. RF power deposition limits vary regionally and with the type of transmit coil used. In commercial systems, methods of calculating power deposition are based on experiments. For this study, we will compare the RF energy of each pulse to that of a nonselective "reference pulse" that has a constant RF amplitude of 14.68 μT for 400 μs, and produces a flip angle of 90°. Using the assumption of a quadrature head coil, and a spherical (0.1 m radius) approximation for the head (25), this pulse deposits an average SAR of 1.4 W/kg (with TR = 5 ms). Our scanner's internal SAR calculation gives 2.2 W/kg for the body coil for a 70-kg patient under the same conditions.

RESULTS

A sample of a standard excitation and minimum-time VERSE RF/gradient waveform pair is shown in Fig. 1. In Fig. 2, we compare slab profiles for TB = 2, TB = 5, and TB = 10 excitations. Both the simulated and experimentally-measured profiles are shown for all three pulses. There is good agreement between the simulations and the phantom measurements. In particular, the TB = 10 pulse produces a very sharp yet flat slab profile.

The simulated profile of the TB = 10 excitation at different resonant frequency offsets is shown in Fig. 3. The slab profile itself is fairly immune to off-resonance. However, there is increased excitation out-of-slab as the resonant frequency offset increases. A sign change in the resonant frequency offset simply flips the slab profile about the origin, as would be expected. In balanced SSFP imaging sequences, a good shim is assumed, so the frequency offsets should not be nearly as large as tested here.

Figure 4 shows the simulated profile of the TB = 10 excitation as the delay between RF and gradient waveforms is changed. For relative delays within 4 μs, the effect on the slab profile is negligible. For symmetric waveforms, as used here, a sign change in the relative delay does not affect the magnitude profile (not shown). Careful tuning of waveform delays allows reduction of inter-waveform delays to within 4 μs.

A sample image showing the profile of an axial slab using a TB = 10 VERSE excitation in vivo is shown in Fig. 5. The contrast is uniform across the slab, and the excitation outside the slab is negligible. This validates the objective of the excitation pulse: the through-slab FOV can be reduced without aliasing.

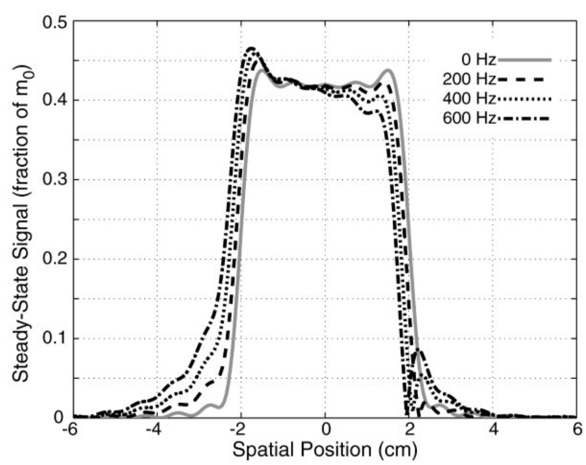

FIG. 3. VERSE TB = 10 profile for resonant offsets of 0 Hz (solid gray line), 200 Hz (dashed line), 400 Hz (dotted line), and 600 Hz (dash-dot line). Note that if the sign of the resonant offset is reversed, the profile is flipped along the position axis. The profiles shown are steady-state slice profiles with TR = 5 ms, so these frequencies correspond to the centers of successive signal "passbands."

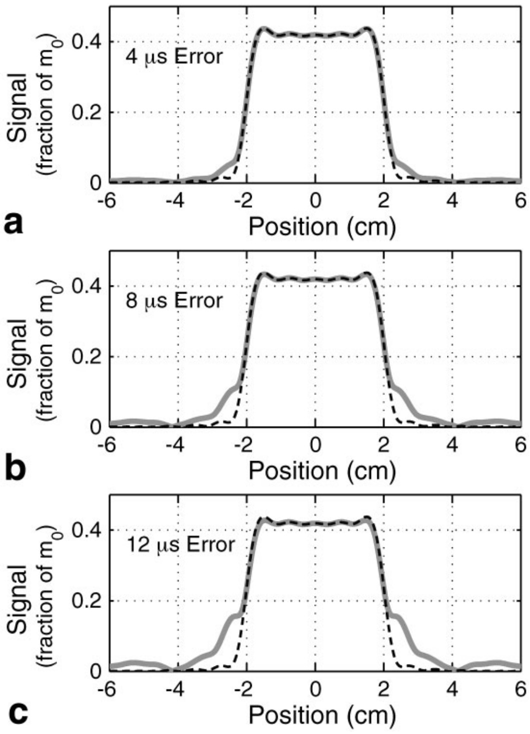

FIG. 4. VERSE TB = 10 (simulated) profile for different timing mismatches between RF and gradient waveforms. Solid gray lines show the profile for timing mismatches of (**a**) 4 μs, (**b**) 8 μs, and (**c**) 12 μs, while the profile with no timing error is shown by the black dashed line in each plot. For waveforms that are symmetric in time, the sign of the delay does not affect the magnitude profile.

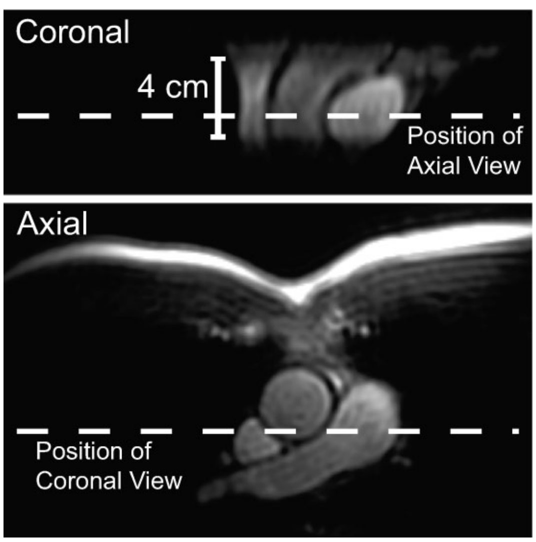

FIG. 5. Coronal (top) and axial (bottom) views from a 3D acquisition slightly above the heart. Images have 2×2×3 mm resolution. The coronal image shows the 4-cm, TB = 10 VERSE slab profile in vivo. The contrast is consistent across the slab, indicating a flat slab profile. The black level is 0 for these images, showing that the FOV could be reduced in the slab direction. As is normal in balanced-SSFP sequences, flow effects do not noticeably degrade the slice profile.

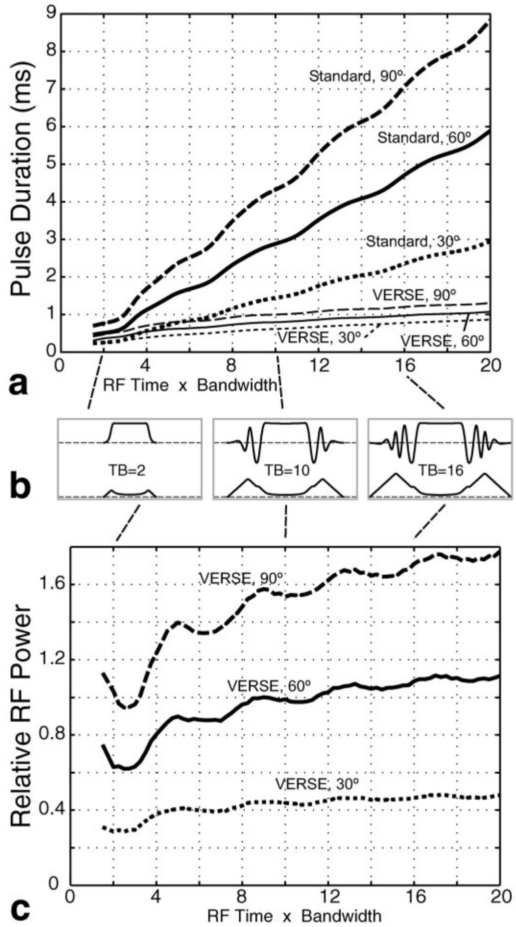

FIG. 6. Duration (**a**), sample waveforms (**b**), and RF energy (**c**) vs. TB of standard and VERSE excitations with flip angles of 30° (dotted lines), 60° (solid lines), and 90° (dashed lines). Standard excitation durations are shown by thicker lines in plot **a**. All pulses assume a maximum RF amplitude of 15 μT, and gradient limits described in the text. For standard pulses, the duration increases roughly linearly with both flip angle and TB. However, for VERSE pulses, the duration is much more favorable in that it is lower to begin with, increases more slowly with flip angle, and tends to flatten as TB is increased. The RF energy scale in plot **c** is relative to a "reference" RF excitation, as described in the text, so that the relative RF power of pulses is preserved for different transmit coils. (The "reference" pulse is a nonselective, 400 μs, 90° pulse.)

The duration of standard and minimum-time VERSE excitations as a function of TB is shown in Fig. 6a. VERSE pulses have a significantly shorter duration than standard pulses. The duration of standard pulses increases roughly linearly with both flip angle and TB. However, the incremental increase in VERSE pulse duration with the flip angle or TB drops as either the flip angle or the TB is increased. This means that VERSE pulses are particularly useful at moderate to high flip angles, or for high-TB excitations.

Figure 6c shows the relative RF energy of 60° minimum-time VERSE excitations compared with that of a "reference" pulse (400 μs, 90°). The RF energy is increased with respect to a nonselective pulse by a factor of almost 2 in the case of a 90° pulse. However, in balanced SSFP, it is

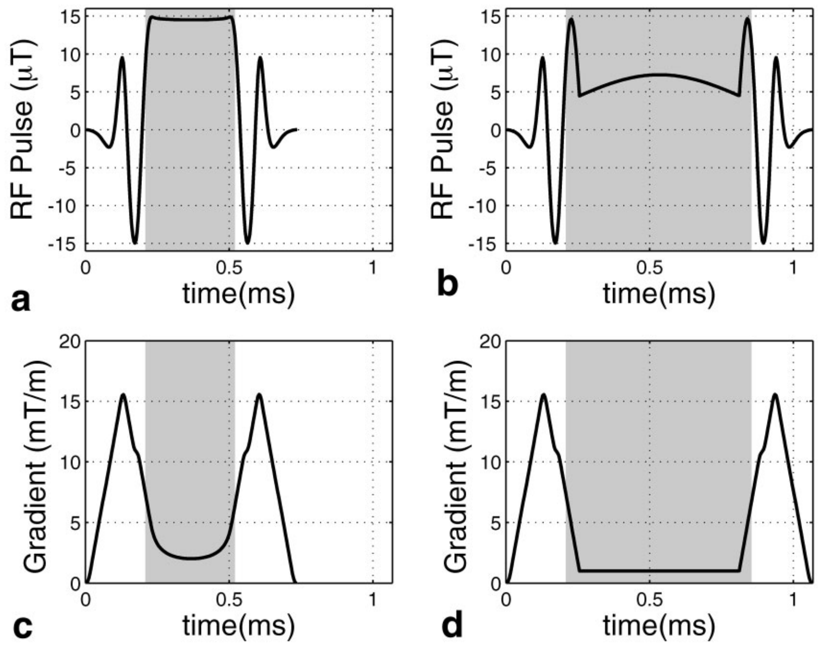

FIG. 7. Minimum-time VERSE TB = 8 RF (**a**) and gradient (**c**) waveforms. Expanded RF (**b**) and gradient (**d**) waveforms are formed by stretching the central lobe of the RF pulse (gray region) by about a factor of 2 in time. Extending the pulse duration by a factor of 1.45 results in a reduction of the RF power by a factor of 1.59. This is a better reduction than the normal case, where stretching a pulse by a factor *R* in time results in a power reduction by the same factor *R*.

typical to use lower flip angles, such as 30–60°. The slope of incremental RF energy with respect to TB drops as TB increases.

DISCUSSION

In this work, we have described a method to design reduced-time excitation pulses that achieve sharp slab profiles for rapid imaging sequences. We validated the pulses in simulations, phantom tests, and in vivo images. In addition, we analyzed the sensitivity of the pulses to resonant frequency offsets and timing mismatches. Finally, we varied the profile sharpness in the design to observe its effect on pulse duration and RF power.

Our design method begins with SLR pulse design (18). The VERSE (8) technique is used to distort the RF waveform to match a time-varying slab-select gradient waveform. We propose a technique that attempts to find the minimum-duration RF and gradient waveforms subject to constraints of maximum RF amplitude, maximum gradient amplitude, and maximum gradient slew-rate. Although it is not rigorously proven that our method results in minimum-duration pulses, it does produce pulses for which one constraint is always active (except at certain points due to low-pass filtering of the gradient). The minimum-duration algorithm takes about 3 s to calculate a 1-ms-duration excitation with 4-μs sample spacing, using Matlab 6.5 (The Mathworks, Natick, MA).

Minimum-time VERSE pulses achieve sharp slab-selective excitation in relatively short amounts of time. Furthermore, the slab sharpness can be further improved with only slight increases in pulse duration, as shown in Fig. 6. As an example with the typical RF and gradient limits used in this study, a 60°, TB = 8 VERSE excitation has a duration of 736 μs. This compares to 2400 μs for a standard TB = 8 excitation, and 233 μs for a nonselective 60° excitation. (This VERSE excitation will be discussed later, and in Fig. 7.)

Compared to standard selective excitation pulses, VERSE pulses can be more sensitive to resonant shifts and RF/gradient timing. In minimum-time VERSE pulses, the gradient amplitude is generally larger than that of the standard excitation. The result is that off-resonance performance is not degraded significantly. Our simulations show that resonant shifts of up to 100 Hz result in a <10% increase in the “out-of-slab” or “stop-band” signal; larger shifts are assumed to be absent in balanced SSFP imaging. We have found that RF/gradient misalignments of up to ±4 ms do not adversely affect the measured profiles. This tolerance in pulse alignment is easily achieved by tuning during the initial pulse sequence testing.

It is possible that a VERSE excitation would be more sensitive to gradient waveform distortion due to amplifier bandwidth limits or to eddy currents. To mitigate the effects of the former, we smoothed the gradient waveforms used on actual scanners before we applied the VERSE algorithm to generate the RF waveform. If necessary, one could correct for both effects by performing a measurement of the *k*-space trajectory using, for example, the method proposed by Duyn et al. (26). The measured *k*-space trajectory could then be used in the VERSE algorithm to shape the RF waveform to match the actual gradient waveform.

All pulses presented in this work meet the typical SAR limits of 4 W/kg at 1.5 T. At higher flip angles, or at higher field strengths, the RF power of these pulses may become a problem. If SAR limits are exceeded, then the pulse can be distorted to reduce SAR. In particular, since most of the energy of the VERSE pulses is in the central lobe, stretching only the central lobe of the RF pulse will significantly reduce the SAR, without much increase in the pulse duration. An example of this is shown in Fig. 7, where the minimum-time TB = 8 VERSE pulse central lobe is expanded by about a factor of 2. The result is a 45% increase in pulse duration that reduces the RF power to 63% of that of the original pulse. Indeed, it would be possible to include the constraint of maximum RF power in a minimum-time VERSE algorithm with the other three constraints (maximum RF amplitude, maximum gradient amplitude, and maximum gradient slew rate). One could also simply repeat the pulse design changing the maximum RF amplitude, until the SAR limit is also met.

The plots of duration and RF power as a function of TB (Fig. 6) show some ripple that is periodic as TB increases by 4. To explain this ripple, consider that a "sinc"-shaped RF excitation pulse has a central lobe, and approximately TB/2-1 sinc-lobes on each side. As TB increases by 2, an additional sinc lobe is added on each side. However, the added lobes alternate between positive and negative lobes. When negative lobes are added, the total power of the pulse tends to increase rapidly, since the main lobe area must increase to preserve RF pulse area. Conversely, when positive lobes are added, the total power increases more slowly, or even drops.

In this work, we assumed a constant limit of 15 μT for the RF amplitude. However, the maximum RF amplitude is dependent on both the type of transmit coil used and the loading of the coil. In typical MR systems, the maximum RF amplitude is determined during a tuning or prescan procedure with the patient in the scanner. The algorithm we used to design the minimum-time VERSE excitations could be applied after this tuning phase, using the measured maximum RF amplitude. This could allow the use of more optimal excitation pulses for certain coils and patients. Additionally, RF power absorption constraints could be applied at this time in the design. Although this modification is probably unnecessary in most cases, it could result in improved performance with pediactric patients or smaller transmit/receive coils.

The minimum-time VERSE algorithm we used in this study is particularly useful for cases in which the RF and gradient waveforms are both well below full-scale for much of the duration of the excitation. Although these pulses are more effective for slab-selective excitation than for thin-slice excitation, there will be cases in which the durations can be reduced for thin slices. Additionally, minimum-time VERSE would be useful for shortening the duration of spatially-selective saturation pulses. In multidimensional pulse design, concepts similar to VERSE have been used to reduce excitation duration (9,27) or RF power (28).

The combination of VERSE slab excitations with balanced SSFP could have many useful applications. For example, in cardiac or abdominal applications (29–31), where patient motion requires rapid scanning, these pulses can enable a reduced FOV in the slab direction. The sharp profiles of these pulses can also benefit balanced-SSFP functional MRI (fMRI) sequences by limiting the FOV to improve temporal resolution (32,33). In all of these applications, the use of sharp slab excitations provides advantages similar to those derived from the use of parallel imaging (34,35). Parallel imaging requires multiple receivers and a more intricate reconstruction, and is limited by coil geometry. The use of a sharp slab excitation is simpler, and allows a more flexible choice of scan plane. Of course, the two methods could also be combined to achieve even faster scans.

The applications described above focus on the use of minimum-time VERSE excitations for balanced SSFP sequences, where shortening the excitation duration by a fraction of a millisecond can provide substantial improvements. In addition to balanced SSFP sequences, these pulses could be useful in other rapid gradient-spoiled and RF-spoiled sequences, but may offer a relatively minor benefit unless a high TB excitation is used.

CONCLUSIONS

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 flip angles are needed across the whole profile to maintain image contrast. While meeting RF amplitude limits, VERSE pulses allow a factor of 3–4 reduction in duration (to <1 ms) for a very sharp slab profile.

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