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Improved Slice-Selective Adiabatic Excitation

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Abstract

Purpose—The purpose of this work is to design an improved Slice-selective Tunable-flip AdiaBatic Low peak-power Excitation (STABLE) pulse with shorter duration and increased off-resonance immunity to make it suitable for use in a greater range of applications and at higher field strengths. An additional aim is to design a variant of this pulse to achieve B_1 -insensitive, fat-suppressed excitation.

Methods—The adiabatic SLR algorithm was used to generate a more uniform spectral pulse envelope for this improved radiofrequency pulse for adiabatic slice-selective excitation, called STABLE-2. Pulse parameters were adjusted to design a version of STABLE-2 with a spectral null centered on lipids.

Results—In vivo images obtained of the human brain at 3 and 7 T demonstrate that STABLE-2 provides robust, uniform, slice-selective excitation over a range of B_1 values. Phantom and in vivo knee images obtained at 3 T demonstrate the effectiveness of STABLE-2 for fat suppression.

Conclusions—STABLE-2 achieves B_1 -insensitive slice-selective excitation while providing greater off-resonance immunity and a shorter pulse duration, when compared to the original STABLE pulse. In particular, the 9.8-ms STABLE-2 pulse provides slice selectivity over 120 Hz whereas the 21-ms STABLE pulse is limited to 80 Hz off-resonance. B_1 -Insensitive fat-suppressed excitation may also be achieved by using a variant of this pulse.

Keywords

adiabatic; Shinnar Le-Roux; RF excitation; STABLE; slice-selective; off-resonance; B_1 -insensitive; fat suppression

INTRODUCTION

Adiabatic radiofrequency (RF) pulses are a powerful means with which to achieve uniform excitation in the presence of a nonuniform B_1 field. Although many alternatives exist for slice-selective adiabatic 180° pulses to refocus or invert magnetization, options for slice-selective adiabatic excitation are more limited (1–3), and require high RF and/or gradient amplitude. A Slice-selective Tunable-flip AdiaBatic Low peak-power Excitation (STABLE) pulse was introduced in 2008 (4), which consists of an oscillating gradient in conjunction with a BIR-4-like RF envelope that is sampled by many short spatial subpulses to achieve spatial selectivity. The pulse functions within gradient and RF amplifier limits of current commercial clinical scanners. However, the long pulse duration of 21 ms and limited off-resonance immunity of 80 Hz make the pulse unsuitable for use in many applications,

especially in the presence of increased B_0 -inhomogeneity at higher field strengths. Recently Moore et al. (5) designed composite pulse envelopes that were numerically optimized to achieve B_1 - and B_0 -insensitivity and sampled these envelopes with spatial subpulses to achieve slice-selectivity. The strategy used to integrate slice-selectivity was very similar to that used for STABLE. Using this numerically optimized approach, Moore et al. achieved shorter pulse duration and consequently greater off-resonance immunity. In this work, we present an analytical method to improve upon the original STABLE pulse. We have modified the BIR-4 envelope with a highly truncated adiabatic SLR (6) spectral RF pulse envelope to reduce the STABLE pulse duration and increase off-resonance immunity. Our redesigned STABLE-2 pulse has a duration of 9.8 ms and off-resonance immunity of 120 Hz. In vivo experiments demonstrate B_1 -insensitivity of the pulse.

Multitransmit systems with custom RF pulses that utilize the “spokes” excitation k-space trajectory have been shown to achieve very uniform transmit B_1 profiles (7–9). This type of setup has been used to obtain in vivo images of the brain at 7 T (10). However, the heterogeneous SAR profiles resulting from multiple RF transmission are not fully understood, currently limiting flip angles to very small values to remain within safety limits. Furthermore, such an approach requires acquisition of subject-specific field maps to generate the custom RF pulses and requires the scanner to be equipped with parallel transmit hardware. Thus, it remains valuable to have single-channel solutions for uniform B_1 -insensitive, slice-selective RF excitation. STABLE-2 offers such a solution.

We also recognized the potential to exploit the intrinsic spectral nulls that occur in the STABLE spectral profile to suppress signal from particular chemical species, such as fat. We redesigned the spectral envelope of the pulse to have a stop-band encompassing the largest lipid resonances at 3 T and tested the performance of this new version of the STABLE-2 pulse in a fat–water phantom and a human knee. Effective B_1 -insensitive fat suppression was achieved by the STABLE-2 pulse.

METHODS

Design Algorithm

Our first step was to design a more uniform spectral adiabatic BIR-4 pulse envelope to reduce the peak RF amplitude of the final STABLE-2 pulse. We used the adiabatic SLR technique described in Ref. 6 to generate an adiabatic full passage pulse. The adiabatic SLR method allows the pulse designer to apply additional quadratic phase across the pulse profile to achieve a more uniform distribution of RF energy.

The adiabatic SLR 180° pulse was designed to have a 516-Hz bandwidth and was truncated to a 4.89-ms duration with a peak RF amplitude of 13 μ T. The pulse waveform was truncated well beyond the 5% of peak amplitude as suggested in Ref. 6, and the spectral profile had low selectivity. However, as the final STABLE-2 pulse is meant to be only slice-selective and not spectrally selective, the spectral selectivity of the adiabatic envelope may be low without deleteriously affecting the off-resonance behavior.

The full passage adiabatic SLR pulse was divided into two half passage segments. As in the conventional BIR-4 design, the spectral envelope was made up of four adiabatic SLR half-passage segments, with the first and third segments being time-reversed. A phase discontinuity was introduced between the first and second segments and between the third and fourth segments to produce the desired flip angle, which was 90°. As in the original STABLE design, the adiabatic spectral envelope was sampled by small tip-angle subpulses to provide spatial selectivity. The subpulses used were windowed sinc pulses with a time–bandwidth product of 3. The number of subpulses was chosen to faithfully sample the

spectral envelope while maintaining long enough subpulse duration to allow accrual of sufficient gradient area to achieve a slice thickness of ~ 5 mm. Nearly triangular gradient lobes and VERSEd (11) subpulses were used to limit the gradient slew rate to remain below gradient hardware and peripheral nerve stimulation (PNS) limits. The resulting spatial bandwidth was 4600 Hz. The final pulse had a duration of 9.8 ms, peak RF amplitude at adiabatic threshold of $13 \mu\text{T}$, 15 spatial subpulses, and slice selectivity over a 120-Hz off-resonance range. As a comparison, the original STABLE pulse had the following pulse parameters: 21-ms duration, 80-Hz off-resonance immunity, peak RF amplitude at adiabatic threshold of $10 \mu\text{T}$, 33 subpulses, a spatial bandwidth of 4300 Hz, and 5-mm minimum slice thickness. The amplitude waveform (with the spectral envelope superimposed for illustrative purposes) and the phase and gradient waveforms for the STABLE-2 pulse are shown in Figure 1.

The RF energy deposition as defined by the specific absorption rate (SAR) value for the 9.8-ms STABLE-2 pulse was calculated and compared to the original 21-ms STABLE pulse presented in Ref. 4. At adiabatic threshold, the SAR for the STABLE-2 pulse was 92% of the SAR of the original STABLE pulse. Profile shape and maximum pulse amplitude at adiabatic threshold are factors determining the calculated SAR value.

Simulations were performed in MATLAB by calculating the Cayley–Klein parameters, α and β , for the piecewise-constant RF pulse as described in Ref. 12. The expressions for the Cayley–Klein parameters represent a series of rotations and may be used to generate the spectral profile for the pulse, which is given by Eq. 1,

$$M_{xy} = (2\alpha^* \beta), \quad [1]$$

where the initial longitudinal magnetization is assumed to be 1. Note that this is equivalent to the calculations performed by a discrete-time Bloch simulator (12)

The 2D simulated spatial-spectral profiles over a 120-Hz and 1000-Hz range in off-resonance are shown for the 90° STABLE-2 pulse in Figure 2a,b. Vertical cross sections through these 2D profiles yield the selected slice at a particular frequency. As shown in Figure 2a, the slice profile remains constant for a ± 60 -Hz shift in resonant frequency.

The simulated slice profile behavior plotted for RF overdrive factors ranging from 1 to 2 is shown in Figure 3. The RF overdrive factor is equal to the amplitude at which we operate the pulse divided by the amplitude of the pulse at adiabatic threshold. Therefore, a RF overdrive factor of 1.2 would mean a 20% increase of pulse amplitude above the adiabatic threshold. The fidelity of the slice is maintained over a 50% increase in B_1 above adiabatic threshold, at which point slight signal loss appears at the center of the profile due to overdriving the subpulses.

Leveraging Nulls for Fat Suppression

The STABLE-2 pulse is not spectrally selective in the way that conventional spatial-spectral (SPSP) excitation pulses (13) or adiabatic 180° SPSP pulses (14) are, as it does not produce a spectral profile with well-defined passbands and stop bands. This is because the adiabatic BIR-4 pulse envelope is nonspectrally selective. However, after the pulse envelope is sampled by spatial subpulses, there is aliasing of the nonselective BIR-4 spectral profiles. Adjacent nonspectrally selective aliased profiles interplay in such a way that there are regions of null signal, which can be leveraged for our purposes. Figure 2b demonstrates distortions in the 2D magnetization profile for STABLE-2, which appear beyond a 120-Hz range of off-resonance. We recognized an opportunity to exploit these frequency ranges

where the profile “pinches” off to create nulls, to suppress signal from chemical species such as fat. We designed a variant of the original pulse design to achieve this purpose.

Targeting implementation at 3 T, we first redesigned the adiabatic SLR spectral envelope to have a 242-Hz bandwidth. This envelope was divided into segments and sampled with subpulses using the same method that is described for the nonselective STABLE-2 pulse. The time-bandwidth product of the subpulses used was reduced to 1 in order to achieve thinner slices at the cost of less spatial selectivity. The pulse duration was decreased to 9.2 ms to further stretch and shift the profile null to be closer to the fat resonance frequency. We also introduced a phase shift in the initial 180° adiabatic SLR waveform to generate a STABLE-2 pulse with a slightly asymmetric 2D spectral profile with a wider stop band on fat. Amplitude and phase waveforms for the selective STABLE-2 pulse for fat-suppressed excitation are shown in Figure 4a,b. The additional phase is evident in the phase waveform plotted in Figure 4b. Figure 5a shows the behavior of the simulated 2D magnetization profile over a 1000-Hz frequency range. There is a stop band in the 2D profile centered at 410 Hz. When using the pulse in a sequence, we shift the transmit frequency by -20 Hz to better encompass the lipid peaks that are centered at ~ 440 Hz at 3 T. This reduces the off-resonance immunity of the excitation passband. However, there is still sufficient undistorted slice-selective behavior over a 100-Hz range in frequencies to excite water adiabatically. Alternatively, we could shorten the pulse duration to stretch out the spectral profile of the pulse, but this would require shorter subpulses and increase the minimum achievable slice-thickness as dictated by gradient limitations. Figure 5b shows the 2D profile for the 200–500 Hz frequency range for several different B_1 amplitudes ranging from 0 to 50% above adiabatic threshold. The lipid stop band becomes appreciably narrower, as B_1 varies beyond 30% above the adiabatic threshold due to bleeding from adjacent side bands.

Experiments to Validate Pulse Performance

In vivo data were initially obtained from the brain of a normal volunteer scanned at 3 T (Echospeed whole-body magnet; GE Healthcare, Waukesha, WI) with a standard birdcage head coil. Axial images of the brain were obtained using the STABLE-2 pulse shown in Figure 1 instead of a conventional windowed sinc pulse for excitation in a gradient-recalled echo (GRE) sequence. Acquisition parameters were: echo time/pulse repetition time (TE/TR) 10/300 ms, 256×128 grid, 2 NEX, 5.5-mm slice, 21×21 cm² FOV, and 1:17 min scan time. Several such images were obtained with the STABLE-2 pulse scaled, in increments of 10%, from 0 to 50% above the adiabatic threshold. Images of the same axial slice through the brain were also obtained using the GRE sequence with B_1 scaled from -20% to $+30\%$ of the nominal pulse amplitude (set at prescan). Variations in signal and contrast with B_1 scaling were compared for images obtained using the two sequences.

In vivo scans were also performed at 7 T (Echospeed whole-body magnet; GE Healthcare) using a Nova Medical (Wilmington, MA) two-channel quadrature transmit and 32-channel parallel-receive head coil. An axial slice through the brain was acquired using the same STABLE-2 sequence as the 3 T scans and a conventional GRE sequence. Acquisition parameters for both scans were: TE/TR: 9/500 ms, 256×256 grid, 1 NEX, 5-mm slice, 22×22 cm² FOV, 2:08 min scan time. The STABLE-2 pulse was scaled, in increments of 10%, to 60% above the RF adiabatic threshold amplitude. A similar experiment was conducted using a standard GRE sequence with a SLR pulse scaled from -40% to $+20\%$ of the nominal pulse amplitude.

A transmit B_1 map of the same slice was obtained using a Bloch–Siegert (B–S) B_1 mapping sequence (15,16) utilizing a 1-ms adiabatic B–S pulse as described in Ref. 17 with the following acquisition parameters: TE/TR: 5/184 ms, FA = 30° , slice thickness = 5 mm and matrix size = 64×64 , FOV = 22×22 cm² and scan time = 50 s. A receive sensitivity map

was also calculated using a method described in Ref. 18, utilizing the measured B-S B_1 map and a gaussian-filtered image (to remove spin density). The conventional GRE and STABLE-2 images were divided by the normalized receive sensitivity to compensate for signal attenuation on the receive side. These receive-compensated images were compared and evaluated for signal and contrast uniformity.

Phantom and in vivo experiments were conducted to verify the performance of the STABLE-2 pulse designed for fat-suppressed excitation. The scans were performed on a 3 T scanner (Echospeed whole-body magnet; GE Health-care) using a GE eight-channel receive/quadrature transmit knee coil. First, a cylindrical phantom containing water and several vials of peanut oil was imaged with a GRE sequence utilizing the STABLE-2 pulse for fat-suppressed excitation and then compared to an image obtained using a conventional GRE sequence. Acquisition parameters were: TE/TR: 9.5/1000 ms, 256×128 grid, 4-mm slice, 22×22 cm² FOV, and 2:08 min scan time. We were able to increase gradient amplitude to achieve 4 mm slice thickness without resulting in PNS due to the reduced time-bandwidth of the subpulses. A frequency offset of -20 Hz was introduced to shift the spectral profile of the pulse, so that the spectral null better encompassed the lipid resonances centered at 440 Hz. Next, we performed a similar experiment in vivo at 3 T. We scanned a knee of a healthy volunteer, so we could assess the effectiveness of the pulse in suppressing fat signal from the bone marrow. As in the phantom experiments, we compared images obtained using STABLE-2 to those obtained using a conventional GRE sequence. We also scaled the STABLE-2 pulse to 25% above adiabatic threshold to test insensitivity to B_1 variation. Acquisition parameters were: TE/TR: 9.5/500 ms, 256×256 grid, 1 NEX, 4-mm slice, 22 × 22 cm² FOV, and 2:08 min scan time.

RESULTS

Figure 6 shows the 3 T axial images of the brain obtained using the STABLE-2 pulse, scaled to several different RF amplitudes. Images obtained using a conventional GRE sequence for a similar range of B_1 amplitudes are also shown. The STABLE-2 images exhibit minimal change in SNR and contrast at different B_1 values, whereas the GRE images suffer from significant signal and contrast variations.

Figure 7a,b shows axial images of the brain obtained using the conventional GRE and STABLE-2 GRE sequences. The B-S B_1 map and the calculated receive sensitivity map of the same slice are shown in Figure 7c,d. All images in Figure 7a have been compensated by the receive sensitivity profile provided in Figure 7d to assess the transmit uniformity of the pulse. The contrast between the gray and white matter in the brain is less for the 7 T images when compared to the 3 T images in Figure 6 due to changes in T_1 as field strength increases. This should be decoupled from the assessment of the transmit uniformity achieved by the RF pulses used.

As seen in Figure 7, the conventional GRE images obtained at 7 T suffer from significant signal and contrast changes in regions where the B_1 field, shown in Figure 7c, reaches its highest and lowest values. Conversely, the STABLE-2 images demonstrate minimal variation, even at the peaks and troughs of the B_1 field map, as RF amplitude is scaled. The first image in the STABLE-2 series suffers some loss in areas of low B_1 , likely because adiabatic threshold is not yet reached in those areas.

Figure 8a shows an axial image of the cylindrical fat-water phantom obtained using a conventional GRE sequence at 3 T. Signal from the fat in the vials is bright and spatially shifted (due to chemical shift) from the water. Figure 8b shows the same slice excited using

the variant of the STABLE-2 pulse with a null on lipid resonances. Fat signal is effectively suppressed.

Figure 9 shows the in vivo knee images obtained at 3 T using a conventional GRE and STABLE-2 sequence. The conventional GRE image in Figure 9a shows fat signal in the marrow of the femur, tibia, and patella. Figure 9b,c shows the same slice of the knee imaged using the STABLE-2 pulse with a null on lipids at the nominal B_1 and 25% above the nominal B_1 . Fat signal in the marrow of the knee bones is largely suppressed, enabling better visualization of the articular cartilage in the knee joint.

DISCUSSION

We have designed the STABLE-2 RF pulse, a shorter, more B_0 -insensitive option for slice-selective adiabatic excitation than the previously proposed STABLE pulse. The shorter pulse duration increases the pulse's applicability by enabling its use in a wider range of pulse sequences and at higher field strengths. Two variants of the STABLE-2 pulse were investigated: (1) a nonselective version that is designed to achieve robust excitation profiles in the presence of B_1 and B_0 inhomogeneity and (2) a selective version that is designed to provide effective fat suppression, while retaining B_1 -insensitive slice-selective excitation.

In vivo data at 3 and 7 T demonstrate that STABLE-2 performs adiabatically over approximately a 50% increase in the B_1 -amplitude above the adiabatic threshold. The pulse is better suited than the previously proposed STABLE pulse (4) for imaging at high magnetic fields, such as 7 T, due to increased robustness to B_0 -shifts and a shorter pulse duration enabling shorter echo times.

Intrinsic nulls in the off-resonance profile were also leveraged to suppress signal from fat in the selective version of the pulse. Phantom and in vivo data at 3 T demonstrate that simultaneous adiabatic slice-selective excitation and fat suppression are achieved by this version of STABLE-2. To use STABLE-2 for fat-suppressed excitation at 7 T, the spectral profile would have to be redesigned to achieve a null at the scaled frequency difference between water and fat, which is ~1026 Hz.

STABLE-2 may provide a valuable B_1 -insensitive alternative to existing fat suppression techniques. A common method for fat suppression is the use of frequency selective presaturation (FATSAT) (19) pulses that are not adiabatic and susceptible to B_1 -inhomogeneity (20). Water excitation using SPSP pulses results in more robust fat-suppression but loss in water excitation efficiency, as the B_1 field varies (21). Short tau inversion recovery (22,23) utilizes an adiabatic 180° pulse for inversion of all spins and delays excitation until an inversion time when fat is passing through a null. Due to the use of an adiabatic pulse, short tau inversion recovery is inherently more resistant to changes in B_1 . However, as fat suppression is achieved by exploiting the differential T_1 value of tissues, SNR efficiency reduces as T_1 values converge with increasing field strength. Spectrally selective adiabatic inversion recovery has been proposed, which does not depend on differential T_1 's but still requires waiting a inversion time prior to excitation (24). B_1 -insensitive RF pulse trains may be used to achieve fat suppression over a limited range of B_1 values, but still require a total duration of 77 ms (25). STABLE-2 offers a B_1 - and T_1 -insensitive option for water only excitation and requires no additional preparation time. STABLE-2 does have the disadvantage of having greater SAR than a FATSAT pulse or conventional SPSP excitation pulse. However, the pulse functioned well within SAR limits at both 3 and 7 T when integrated into a GRE sequence with a 500-ms TR, as shown in the "Results" section. Also, narrowing of the lipid spectral stop band beyond a 30% increase in B_1 -amplitude above the adiabatic threshold results in incomplete fat suppression for

STABLE-2. Further exploration of new spectral envelopes with a wider stop band on lipids would make this a more robust fat suppression technique.

We investigated the 2D magnetization profile of STABLE pulses for flip angles below 90° and found that off-resonance immunity for all STABLE designs is reduced for excitation flip angles below 90° . Figure 10 shows the simulated slice profile versus off-resonance frequency for a 45° STABLE-2 pulse. The pulse was created by reducing the phase offset between adiabatic half-passage pulse segments to equal the desired flip angle. As the off-resonance frequency approaches ± 60 Hz, distortion lobes appear in the 2D profile and the excited magnetization gradually increases to 100%, which deviates from the expected flip angle. Therefore, the pulse only provides the expected flip angle over a narrower frequency range of ~ 50 Hz.

Limited off-resonance immunity is an intrinsic disadvantage of STABLE pulses. The use of insert gradients may allow shorter pulse duration, thereby increasing the frequency range over which undistorted slice-selection is achieved. A higher gradient maximum amplitude and slew rate will also enable thinner minimum slice thickness. However, for some subjects, PNS may occur before reaching these limits. Due to the use of short subpulses to achieve slice selection in all STABLE designs, exciting thin slices remains a challenge. Slice selectivity may also be traded off with slice thickness, that is, subpulses with lower spatial bandwidth may be used to generate thinner slices with less sharp edges. This technique was employed in the version of STABLE-2 for fat suppressed excitation.

STABLE, STABLE-2, and the numerically optimized slice-selective composite pulses proposed by Moore et al. (5) are all part of a family of SPSP-like nonlinear phase pulses, which exhibit adiabatic and slice-selective behavior. The pulses by Moore et al. achieve many of the same design goals as STABLE-2 and offer a powerful alternative for B_1 -insensitive excitation. We expect that there probably exist more RF pulses that are members of this family that remain to be explored. Similar limits exist on the slice thickness that may be achieved by these pulses, as slice thickness is determined by the subpulse spatial bandwidth and the strength of the gradients used. Moore et al. explored gaussian and sinc subpulses and operated at gradient limits to achieve slices as thin as 2 mm. In the design of STABLE-2, different subpulse waveforms were not fully explored to decrease slice thickness. However, subpulses can easily be adjusted within this design framework to explore these trade offs. Moore et al. were successful in shortening pulse duration to 5 ms and achieved slice-selective behavior over a 200-Hz range with similar B_1 -immunity but less selective slice profiles than STABLE-2. As STABLE-2 enforces an adiabatic envelope, it is challenging to reduce pulse duration to 5 ms without increasing peak RF amplitude to prohibitively high values. This may be an inherent disadvantage of STABLE-2 when compared to the composite pulses by Moore et al. However, the fact that STABLE-2 uses an adiabatic BIR-4 envelope, which is systematically generated by the adiabatic SLR algorithm (6) makes it possible for the pulse designer to have greater control over the final shape of the spatial-spectral profile. The fat-nulling version of STABLE-2 presented in this work is an example of how pulse parameters may be adjusted to predictably change profile shape.

Contrast differences due to the spin-locked state of the magnetization during the STABLE-2 pulse were not explored in this study. These differences are less pronounced than those observed for the original STABLE pulse due to the shorter duration of the pulse. However, they remain a subject of future study.

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FIG. 1. RF (a) amplitude, (b) phase, and (c) gradient waveforms for the STABLE-2 RF pulse. In (a), the spectral envelope composed of truncated adiabatic SLR pulse segments is overlaid on the RF pulse amplitude as a dotted line.

FIG. 2. 2D plots of slice profile versus off-resonance frequency over (a) a 120-Hz range and (b) a 1000-Hz range.

FIG. 3. Simulated slice profile produced by a 9.8-ms STABLE-2 pulse for a range of B_1 amplitudes. The B_1 overdrive factor is equal to the amplitude at which we operate the pulse divided by the amplitude of the pulse at adiabatic threshold. Some loss at the center of the slice profile occurs at larger B_1 values.

FIG. 4. RF (a) amplitude and (b) phase waveforms for STABLE-2 RF pulse designed for fat-suppressed excitation. An adiabatic SLR envelope with a lower spectral BW is used to enlarge the nulls in the profile.

FIG. 5.

2D plots of simulated slice profile versus off-resonance frequency for STABLE-2 RF pulse designed for adiabatic fat-suppressed excitation. **(a)** Slice profile over a 1000-Hz frequency range showing a stop band/null in the profile used to suppress lipid signal at 3 T. **(b)** Slice profile zoomed in to frequencies ranging between 200 and 500 Hz for the pulse scaled to several different B_1 values above adiabatic threshold. This version of the STABLE-2 pulse adiabatically excites water while suppressing lipids.

FIG. 6.

In vivo axial images of the brain of a normal volunteer obtained at 3 T using the STABLE-2 pulse in a GRE sequence to excite and image a 5.5-mm slice ($TE/TR = 10/300$ ms). Several such images were obtained with the STABLE-2 pulse scaled from 0 to 50% above the adiabatic threshold. Images were also obtained using the GRE sequence with B_1 scaled from -20% to +30% of the nominal pulse amplitude.

FIG. 7.

In vivo axial images of the brain of a normal volunteer obtained at 7 T using the STABLE-2 pulse in a GRE sequence to excite and image a 5-mm slice ($TE/TR = 9/500$ ms). **a:** Images obtained using the GRE sequence with B_1 scaled from -40 to $+20\%$ of the nominal pulse amplitude. **b:** Images obtained with the STABLE-2 pulse scaled from 0 to 60% above the adiabatic threshold. Image intensity was compensated by the measured receive B_1 profile shown in **(d)**. Significant B_1 -sensitivity, which follows the measured transmit B_1 profile shown in **(c)**: is noticeable as signal and contrast variation in the GRE images, while the STABLE-2 images remain fairly invariant in the presence of B_1 variation.

FIG. 8.

Image of a slice through a cylindrical water phantom containing several vials of oil obtained at 3 T using (a) a standard GRE sequence and (b) the 90° STABLE-2 pulse used for fat-suppressed excitation in a GRE sequence. Scan parameters for both sequences were TE/TR: 9.5/1000 ms, 256×128 grid, 4-mm slice, 22×22 cm² FOV, and 2:08 min scan time. Spatially shifted fat signal is visible in the GRE sequence, whereas fat is suppressed in the STABLE-2 image.

FIG. 9.

In vivo knee images obtained at 3 T using (a) a standard GRE sequence and a GRE sequence using a 90° STABLE-2 RF pulse designed with a null on the lipid resonances, set to (b) the nominal B_1 at prescan, and (c) 25% greater than the Nominal B_1 . Scan parameters for both sequences were TE/TR: 9.5/500 ms, 256×256 grid, 4-mm slice, 22×22 cm² FOV, and 2:08 min scan time. The white arrow indicates fat in the bone marrow, which appears dark against bright articular cartilage in both STABLE-2 images, demonstrating B_1 -insensitive fat suppressed excitation.

FIG. 10. Simulated slice profile versus off-resonance frequency for STABLE-2 RF Pulse designed for a 45° excitation flip angle. The desired flip angle is achieved for approximately a 50-Hz range in off-resonance.