Technical Note: The effect of 2D excitation profile on T₁ measurement accuracy using the variable flip angle method with an average flip angle assumption

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Purpose: To study the accuracy and precision of T₁ estimates using the Variable Flip Angle (VFA) method in 2D and 3D acquisitions.

Methods: Excitation profiles were simulated using numerical implementation of the Bloch equations for Hamming-windowed sinc excitation pulses with different time-bandwidth products (TBP) of 2, 6, and 10 and for T₁ values of 295 ms and 1045 ms. Experimental data were collected in 5° increments from 5° to 90° for the same T₁ and TBP values. T₁ was calculated for every combination of flip angle with and without a correction for B₁ and slice profile variation. Calculations were also made for flat slice profile such as obtained in 3D acquisition. Monte Carlo simulations were performed to obtain T₁ measurement uncertainty.

Results: VFA T₁ measurements in 2D without correction can result in a 40–80% underestimation of true T₁. Flip angle correction can reduce the underestimation, but results in accurate measurements of T₁ only within a narrow band of flip angle combinations. The narrow band of accuracy increases with TBP, but remains too narrow for any practical range of T₁ values or B₁ variation. Simulated noisy VFA T₁ measurements in 3D were accurate as long as the two angles chosen are on either side of the Ernst angle.

Conclusions: Accurate T₁ estimates from VFA 2D acquisitions are possible, but only a narrow range of T₁ values within a narrow range of flip angle combinations can be accurately calculated using a 2D slice. Unless a better flip angle correction method is used, these results demonstrate that accurate measurements of T₁ in 2D cannot be obtained robustly enough for practical use and are more likely obtained by a thin slab 3D VFA acquisition than from multiple-slice 2D acquisitions. VFA T₁ measurements in 3D are accurate for wide ranges of flip angle combinations and T₁ values.

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Key words: 2D excitation profile, slice profile, T₁ measurement, variable flip angle

1. INTRODUCTION

The longitudinal relaxation time T₁ is an intrinsic property of tissues and changes with water content, temperature, relaxation agents, local molecular environment, and main magnetic field strength.^{1,2} The dependence of T₁ on different physical properties makes T₁ mapping useful for several fields of interest, including dynamic contrast-enhanced studies of tissue perfusion,^{3,4} diagnosis of neurological diseases,⁵ MRI thermometry,⁶ and digestive transport.⁷

There are several methods for T₁ measurement, most of which are relatively slow (e.g. Ref. 8–10). The Variable Flip Angle (VFA) method, which is examined in this work, is based on the relationship of the measured steady-state signal to repetition time (TR), T₁, and flip angle.¹¹ The basic implementation of this method is to acquire signal from two scans with the exact same parameters, except flip angle, and then use the spoiled gradient recalled (SPGR) steady-state signal equation to calculate T₁ (see Section 2). When only using two flip angles, the theoretical optimal choices of flip angles are those that give approximately 71% of the maximum signal at the Ernst angle.¹² The first implementation of the VFA

method was performed using a 2D acquisition.¹¹ Most VFA T₁ measurement studies have been performed using 3D acquisitions,^{12–16} but to decrease acquisition time, the VFA method could be performed in 2D. A major source of error when using VFA method is variations in transmit radiofrequency (RF) field, which occurs from tissue dielectric effects.^{17,18} In this work, it is assumed that the actual flip angle is linearly dependent on the strength of the transmit RF field, and therefore, a linear correction can be used.^{19,20}

In addition to variations in the transmit RF field, another major source of error in 2D acquisitions is the nonuniform slice excitation profile which causes a large variation in flip angle within every single voxel. Truncated RF pulse envelopes cause the slice profile to vary from the ideal rect function, which leads to the edges of the slice experiencing a lower flip angle than prescribed. Prescribing flip angles larger than the Ernst angle creates a steady-state slice profile with large signal contribution from the edges of the slice, which experienced less than the prescribed flip angle. The variation in RF excitation profile is less of a problem in 3D acquisitions, because any slice near the center of the 3D slab (away from the edge of the slab) will experience very little

flip angle variation across the slice and the signal will follow the theoretical SPGR relationship. The nonuniform slice excitation profile problem was examined by Parker et al.²⁰ as they studied measuring T₁ in 2D acquisitions using a dual acquisition method similar to VFA where TR was varied instead of flip angle. They created a lookup table to map the transmit RF field, and a lookup table to calculate T₁ based on a ratio of the signal magnitudes from the two different TR scans. Their method required one of the TR values to be much longer than the other, increasing total scan time, as well as creating a lookup table for RF field and a lookup table for the signal ratios using the two TR values. If different TR values were used, a new lookup table would be required.

The purpose of this study was to evaluate the dependence of the signal equation on the excitation profile and determine the resulting accuracy and precision in T₁ measurements in 2D acquisitions using the VFA method. The slice excitation profile was simulated using numerical solutions of the Bloch equations to develop a model of the signal dependence to the RF excitation pulse properties. This model was tested with simulations and experiments.

2. THEORY

The VFA method for measuring T₁ makes use of the spoiled gradient recalled (SPGR) steady-state signal equation

$$S = gM_0 \frac{(1 - E_1)\sin(\alpha)}{1 - E_1\cos(\alpha)} E_2 \quad (1)$$

where $E_1 = \exp(-TR/T_1)$ and $E_2 = \exp(-TE/T_2^*)$. Here, M_0 is the equilibrium magnetization, g is a spatially varying scale factor, α is the flip angle, TR is the pulse repetition time, TE is the sequence echo time, and T₁ and T₂^{*} are the longitudinal and transverse relaxation times. The value of g is dependent on the coil sensitivities which are spatially dependent. The flip angle α can also be spatially dependent through inhomogeneities in the RF transmit field. This equation is derived assuming that $TR \gg T_2^*$, or adequate spoiling is used to ensure that negligible transverse signal remains before subsequent excitations. If these conditions are not met, Eq. (1) will not accurately describe the signal, and significant errors in T₁ calculation will occur. Eq. (1) rewritten in linear form is¹¹

$$\frac{S}{\sin(\alpha)} = E_1 \frac{S}{\tan(\alpha)} + M_0(1 - E_1)E_2. \quad (2)$$

Calculation of T₁ is done by acquiring the signal at a minimum two different flip angles and fitting a line to $S/\sin(\alpha)$ vs. $S/\tan(\alpha)$ to determine the slope m . This slope is equal to E_1 and thus T₁ is calculated using

$$T_1 = \frac{-TR}{\ln(m)} \quad (3)$$

2.A. Flip angle correction method

In an attempt to deal with the nonuniform excitation profile across the slice, it is often assumed that the signal

depends linearly on an average or effective flip angle.^{20,21} This linear assumption allows for attempted correction of the slice profile at the same time as correction of the transmit RF error using the same technique. The assumption of an average flip angle may work well for small angles, but the accuracy will decrease as the angle increases and will be poor for angles that exceed the Ernst angle due to the extra signal contribution from edges of the slice [Fig. 1(c)]. The amount of extra signal depends on the shape of the slice profile, which depends on the RF pulse properties [Fig. 1(b)].

The 2D flip angle correction method for both RF transmit inhomogeneity and average flip angle across the slice profile used in this study is the same method employed by Todd et al.²¹ The signal vs. flip angle data were fit to Eq. (1) using a least-squares fit with the known/measured

FIG. 1. Simulated slice excitation profiles for various time-bandwidth products (TBP). Real component (solid) and imaginary (dashed). Black vertical bars show the desired slice thickness of 3 mm. Comparison of TBP 2, 6, 10 at 90° flip angle, TR = 20 ms, T₁ = 295 ms for (a) initial excitation profile (b) and steady-state profiles. (c) Comparison of steady-state profile for TBP 6 at various flip angles. [Color figure can be viewed at wileyonlinelibrary.com]

T_1 values and user-defined TR value with free parameters M_0 and c , where c is defined by $\alpha_a = c \cdot \alpha_p$, and where α_a is the estimate of the actual/average flip angle, α_p is the prescribed flip angle, and c is the flip angle correction value. An accurate estimate of T_1 is required for this fit. Because this method assumes a linear relation between the prescribed and actual flip angles, it works well for RF transmit inhomogeneity, but is only an approximation for the nonlinear relationship of the excitation profile within a voxel across the slice.

3. METHODS

3.A. Simulations

Simulations were performed to analyze the effects of the slice excitation profile on the accuracy of T_1 measurements using the VFA method. The initial excited magnetization profile was calculated using a numerical implementation of the Bloch equations to simulate the effects of the excitation pulse and slice select gradient. The shape of the magnetization profile after excitation is dependent on several factors including the prescribed flip angle α , the TR/ T_1 ratio, and the time-bandwidth product (TBP) of the excitation pulse. (TBP is defined as the product of the pulse bandwidth and pulse duration.) Therefore, simulations were performed for flip angles 1° through 90° in 1° increments, for TBP 2, 6, and 10, and $T_1 = 295, 1045$ ms (values chosen to match the experiment described below). All simulations used a TR of 20 ms, slice thickness of 3 mm, and RF pulse duration of 4 ms. To maintain RF pulse duration and slice thickness as constant, the desired TBP was achieved by changing the bandwidth and amplitude of the RF pulse as well as the amplitude of the slice selection gradient, as is typically done in practice.

To simulate the excitation profile, the free precession and rotation caused by a Hamming-windowed sinc excitation pulse and slice select gradient were simulated as they are played out in time, for each position in the slice. The dependence of the magnetization on T_1 and T_2 is assumed to be negligible during the time of RF pulse. Because the nominal (prescribed) flip angle is only achieved near the center of the slice, the actual flip angle achieved at each slice position is found by

$$\alpha(z) = \tan^{-1} \frac{\sqrt{M_x(z)^2 + M_y(z)^2}}{M_z(z)} \quad (4)$$

where $M_x(z)$, $M_y(z)$, $M_z(z)$ are the x, y, and z components of the magnetization vector.

Simulation of the steady-state signal for each magnetization profile was done using the same method as Parker et al.²⁰ The total signal measured is the integral of Eq. (1) over the whole slice thickness, but because there is signal contribution from both $M_x(z)$ and $M_y(z)$, Eq. (1) must be modified to include the phase of the transverse magnetization, $\Phi(z)$,

$$M_x = A \int_{\text{slice}} \left\{ \frac{(1 - E_1) \sin(\alpha(z)) \cos(\Phi(z))}{1 - E_1 \cos(\alpha(z))} \right\} dz \quad (5)$$

$$M_y = A \int_{\text{slice}} \left\{ \frac{(1 - E_1) \sin(\alpha(z)) \sin(\Phi(z))}{1 - E_1 \cos(\alpha(z))} \right\} dz \quad (6)$$

where A is a constant of proportionality. Discretizing these two integrals over the slice profile, and assuming the signal is directly proportional to transverse magnetization, gives

$$S_x = A \sum_{n=1}^N \left\{ \frac{(1 - E_1) \sin(\alpha(n)) \cos(\Phi(n))}{1 - E_1 \cos(\alpha(n))} \right\} \Delta z \quad (7)$$

$$S_y = A \sum_{n=1}^N \left\{ \frac{(1 - E_1) \sin(\alpha(n)) \sin(\Phi(n))}{1 - E_1 \cos(\alpha(n))} \right\} \Delta z \quad (8)$$

where S_x and S_y are the real and imaginary components of the signal, N is the number of equally spaced discrete samples indexed by n , and Δz is the spacing between samples. For this study, we used $N = 1201$ over a slice profile from $z = -6$ mm to $z = +6$ mm. The total signal is

$$S = \sqrt{S_x^2 + S_y^2}. \quad (9)$$

The integrated signal for the imaginary components, Eqs. (6) and (8), is equal to zero for the pulse used, because the imaginary component is antisymmetric as seen in Fig. 1. This is not always the case, as it depends on the axis of rotation and the properties of the RF pulse.

T_1 values were calculated for simulation and experimental data using the VFA method for every combination of flip angles and compared with the true values. T_1 values were also calculated using the VFA method with corrected flip angles using the correction technique described above. For comparison, the theoretical average flip angle across the slice was calculated by averaging all flip angles across the slice that were at least 5% of the prescribed angle (Table I).

To simulate the sensitivity of T_1 measurements to errors, noisy measurements were simulated using a Monte Carlo technique. Complex white Gaussian noise of constant power was added to the complex signal profile before integration;

TABLE I. Calculated flip angle correction values c as a ratio to the prescribed angle for each time-bandwidth product (TBP) and T_1 value for simulated and experimental data compared to the theoretical average flip angle across the slice profile.

	$T_1 = 295$ ms		$T_1 = 1045$ ms		Theoretical average ratio from slice profile
	Simulation	Experiment	Simulation	Experiment	
TBP 2	0.527	0.481	0.423	0.495	0.613
TBP 6	0.726	0.643	0.649	0.746	0.775
TBP 10	0.836	0.731	0.811	0.922	0.811

3000 noisy signals were generated, and T₁ estimates were calculated for every combination of flip angle, using the flip angle correction technique described above, for each noisy signal. The standard deviation (σ_{T_1}) at each flip angle combination was calculated from the 3000 estimates. The noise power is the same for all simulations, but the lower TBP will have a higher signal-to-noise ratio (SNR) than higher TBPs in 2D, because the imperfect excitation profile produces a thicker slice leading to more signal contribution. Therefore, to normalize the results to SNR (σ_{norm}), the fractional error (σ_{T_1}/T_1) is multiplied by the maximum SNR.

$$\sigma_{norm} = \frac{\sigma_{T_1}}{T_1} * SNR \quad (10)$$

3.B. 3D VFA T₁ simulations

For comparison, the same Monte Carlo simulations were performed for the center slice of a 3D acquisition. The standard deviation normalized to SNR for T₁ = 295 and 1045 ms was calculated. Simulated noise values giving an approximate SNR of 200, 20, and 10 at the Ernst angle were used to calculate the average accuracy of 3D VFA T₁ measurements in the presence of noise by taking the mean value of T₁ measurements from 3000 noisy signals for every combination of flip angles.

3.C. Experiment

All experimental data were acquired using a Siemens Tim Trio 3T MRI scanner and the magnet's volumetric body coil for RF transmit and receive to ensure nearly uniform receive sensitivity across the image. An experiment was performed to acquire signal vs. flip angle data for TBP = 2, 6, and 10 in 2D using a homogeneous gelatin phantom and vegetable oil at flip angles in 5° increments from 5° to 90°. A GRE sequence capable of changing TBP while maintaining constant pulse duration was used (scan parameters: 3 × 3 × 3 mm resolution; TR/TE = 20/6 ms; FOV 384 × 168 mm; 9 averages). Signal values were averaged over a 3 × 3 ROI near the center of both the gelatin and oil. Inversion recovery (IR) data (3 × 3 × 3 mm resolution; TR/TI = 20000/25, 50, 75, 100, 150, 200, 250, 300, 400, 500, 650, 800, 1000, 1300, 1700, 2400, 3500, 5500, 10000 ms; FOV 384 × 168 mm) were collected to accurately calculate T₁ using the inversion recovery (IR) method²² to compare with values calculated using the VFA method, and for use in the flip angle correction.

4. RESULTS

The real and imaginary excitation profile simulation results are shown in Fig. 1. For prescribed flip angles larger than the Ernst angle, the imperfect slice profile leads to signal contribution from the outer regions of the slice which experienced flip angles less than the prescribed flip angle.

In comparing the simulation and experiment in Figs. 2(a) and 2(d), it appears that both the oil and gelatin phantoms experienced slightly smaller RF amplitudes than the corresponding values used in the simulations. The simulated and experimental curves agree better after flip angle correction as shown in Figs. 2(b) and 2(e). Figures 2(c) and 2(f) show the signal normalized to maximum value vs. flip angle using flip angle correction for simulations with TBP 2, 6, and 10 as well as the expected SPGR steady-state signal [Eq. (1)]. Equation (1) does not accurately describe the total signal as a function of flip angle in 2D acquisitions. The 2D signal vs. flip angle relationships is much closer to the steady-state equation when the flip angle correction is used. The calculated flip angle correction factor for each case is given in Table I.

Figure 3 shows the simulated T₁ estimates calculated without flip angle correction as percent of the true T₁, and the experimental results are shown in Fig. S1. Note that for nearly all flip angle and TBP combinations, the VFA method severely underestimates T₁. While some combinations in this band produce accurate T₁ estimates, it should be noted that no noise has been added to the simulations at this point. Once noise is added, measurements of T₁ at these combinations are unreliable.¹²

Figure 4 shows the simulated T₁ estimates calculated with flip angle correction as a percent of the true T₁, and the experimental results are shown in Fig. S2. While accurate measurements of T₁ can be obtained from multiple combinations, these results depend heavily on the TR/T₁ ratio and TBP. A decrease in T₁ or an increase in TR will increase the number of combinations leading to accurate T₁ estimates; also, as TBP increases, the range of combinations resulting in an accurate T₁ also increases. This increased range in flip angle combinations also adds a little more “forgiveness” to slightly incorrect choice in angles. The combinations giving reasonable T₁ values are outlined with white lines, which is arbitrarily set to be between 95% and 105% of the true value.

Results of the Monte Carlo simulation for 2D and 3D acquisitions are shown in Fig. 5, and the experimental results are shown in Fig. S3. The ratio of standard deviation to true T₁ (σ_{T_1}/T_1) is inversely proportional to the SNR. Therefore, results are displayed as maximum SNR times the fractional error in T₁ to demonstrate measurement precision for any SNR. The flip angle combination that gave the highest precision is marked with a red x, and in every 2D case was not the same combination as the most accurate. Finally, for comparison, results are shown for T₁ measurement accuracy using 3D acquisition, with SNR values of 200, 20, and 10 (Fig. 6). The average accuracy of simulated noisy 2D acquisitions with SNR values of 10 is shown in Fig. S4.

5. DISCUSSION

This article has considered the problem of using the variable flip angle method in conjunction with 2D or 3D acquisitions to make quantitative measurements of the longitudinal

FIG. 2. Comparison of total signal vs. flip angle from Bloch simulations (dash) to experimental data (solid) for TBP 2, 6, 10 using (a–c) vegetable oil ($T_1 = 295 \pm 5$ ms) and (d–f) gelatin phantom ($T_1 = 1045 \pm 10$ ms). (b, c, e, f) Signal vs. flip angle using corrected flip angle values. (c, f) Normalized flip angle corrected simulated signal compared with theoretical SPGR signal, Eq. (1). [Color figure can be viewed at wileyonlinelibrary.com]

FIG. 3. Bloch simulation calculations of T_1 for every combination of flip angles without flip angle correction displayed as percent of true T_1 . (a–c) $T_1 = 295$ ms and (d–f) $T_1 = 1045$ ms. (a, d) TBP 2, (b, e) TBP 6, (c, f) TBP 10. [Color figure can be viewed at wileyonlinelibrary.com]

relaxation time, T_1 . In 2D acquisition, the nonrectangular excitation profile leads to signal contribution from the outer edges of the slice, which experience a flip angle less than the prescribed angle. This signal contribution increases with flip angle and becomes significant when the prescribed angle is larger than the Ernst angle. This extra signal creates a total signal vs. flip angle relationship that is not accurately described by the SPGR steady-state signal equation and, therefore, introduces errors in measurements of T_1 , even at

low flip angles combination as seen in Fig. 3. Although the slice profile can affect the edge slices in a 3D acquisition, the central slices generally have very little through plane slice profile variation.

The flip angle correction technique used, which assumes that the total signal in the slice is based on the average flip angle experienced in the slice, attempted to correct for the imperfect slice excitation profile. The correction based on the average flip angle assumption was only partially effective,

FIG. 4. Bloch simulation calculations of T_1 for every combination of flip angles using flip angle correction displayed as percent of true T_1 . (a–c) $T_1 = 295$ ms and (d–f) $T_1 = 1045$ ms. (a, d) TBP 2, (b, e) TBP 6, (c, f) TBP 10. Flip angles shown are the prescribed flip angle. The white lines outline the flip angle combinations that produce T_1 values within $\pm 5\%$ of the true value. [Color figure can be viewed at wileyonlinelibrary.com]

FIG. 5. Normalized standard deviation of T_1 [σ_{norm} from Eq. (10)] from Monte Carlo simulations for every combination of flip angles using flip angle correction for 2D and no correction for 3D acquisition. (a–d) $T_1 = 295$ ms and (e–h) $T_1 = 1045$ ms. (a, e) TBP 2, (b, f) TBP 6, (c, g) TBP 10, (d, h) 3D Slice. Flip angles shown are the prescribed flip angle. White lines outline the flip angle combinations that produce T_1 values within $\pm 5\%$ of the true value. Red x's indicate the flip angle choices with the best precision. [Color figure can be viewed at wileyonlinelibrary.com]

which is shown in Figs. 2c and 2f. This correction technique, which is generally used to correct for variations in flip angle due to RF transmit inhomogeneity, only resulted in accurate T_1 measurements within a narrow band of angle combinations. An unfortunate result of the limited choices for

accurate flip angle combinations means that tissues with large T_1 differences cannot be accurately measured using the same flip angles in a 2D scan. This also results in the conundrum that T_1 can only be measured accurately if the approximate value of T_1 is known.

FIG. 6. Simulated accuracy of T_1 using a 3D acquisition with $T_1 = 295$ ms in the presence of noise for every combination of flip angles displayed as percent of true T_1 . Noise added to give SNR of (a) 200, (b) 20, and (c) 10 at Ernst angle. White lines outline the flip angle combinations that produce T_1 values within $\pm 5\%$ of the true value. [Color figure can be viewed at wileyonlinelibrary.com]

For 2D measurements using flip angle correction, the accuracy and precision of T_1 measurements are both dependent on the two flip angles used, as well as the TR/ T_1 ratio and the TBP. Increasing TR and/or TBP leads to a wider band of flip angle combinations that result in accurate estimates of T_1 . Thus, the best choice of flip angles in a 2D acquisition must be considered in terms of accuracy in addition to precision, which are not near the 71% of maximum. For example, for TBP = 2, the total signal never reduces to 71% of the maximum by 90° , yet can still result in accurate (e.g., $\pm 5\%$) measurements of T_1 within a narrow band of flip angle combinations. A general trend that is observed is that the optimum flip angles are both larger than those used in an equivalent 3D measurement. For example, in terms of both accuracy and precision, the optimum prescribed (uncorrected) flip angles for TBP = 10 and $T_1 = 295$ ms are 14° ($\sim 87\%$) and 70° ($\sim 63\%$), and for the ideal SPGR (rectangular slice profile), they are 9° and 49° (both $\sim 71\%$). Similar to 3D VFA, the error is largely determined by the smaller of the two flip angles.¹² A larger TBP requires a larger amplitude RF pulse and a larger slice select gradient to achieve the same desired slice thickness using the same pulse duration. As specific absorption rate (SAR) increases with the square of the pulse amplitude, a trade-off between desired slice profile and SAR needs to always be considered.

The initial investigation of the VFA technique by Fram et al.¹¹ was done with a single slice. At that time, their largest source of error was the incomplete spoiling of the residual magnetization, resulting in significant error in T_1 due to the deviation in signal from the SPGR equation. They recognized a residual nonlinearity in their plots of $\text{signal}/\sin(\alpha)$ vs. $\text{signal}/\tan(\alpha)$ including the variation in signal across the slice as one of the possible causes. Plots of the simulated data from Fig. 2 as $\text{signal}/\sin(\alpha)$ vs. $\text{signal}/\tan(\alpha)$ (not shown) have the same nonlinearity, strongly indicating that their observed residual nonlinearity was in fact due to the nonuniform slice excitation profile.

The correction method presented here assumes a linear relationship between the prescribed flip angle and the

effective flip angle. More accurate T_1 calculations might be possible if a more exact, nonlinear, relationship could be developed and used. Although the results were also limited to just two T_1 values, it is believed that these results are indicative of the types of errors that would be obtained for a range of T_1 values.

We note that our simulation and experimental results are specific to the Hamming-windowed sinc RF pulse envelope and resulting profile shape considered in this paper, and are only an example of the errors that can occur with different RF pulse envelopes that have different profiles. But all finite duration pulses will have some nonuniformity in excitation profile and will, therefore, result in measurement errors. The results presented are qualitatively indicative of the errors that can be expected.

The slice excitation profile is an important factor in the accuracy of T_1 measurements using the VFA method in a 2D acquisition. T_1 measurement errors occur due to the large flip angle variation within each voxel of the 2D slice. The flip angle correction method detailed here compensates for RF transmit inhomogeneity as well as providing a first-order compensation for the error due to the imperfect slice excitation profile. Even with this correction, only a narrow band of angle combinations results in accurate T_1 . As TBP increases, the band of accurate flip angle combinations widens. Only a narrow range of T_1 values can be accurately calculated using a single combination of flip angles in a 2D slice.

6. CONCLUSIONS

Although this article demonstrates that accurate values of T_1 can be obtained using the VFA method in 2D, these accurate values are only obtained in a narrow band of flip angle combinations while using a specific flip angle correction method. These results also show that only a narrow range of T_1 values can be accurately determined using a single combination of flip angles in 2D. Large errors will occur if there are variations in the flip angle across the slice. That is, simply correcting for the variations in RF transmit throughout the

slice does not compensate for regions in the slice where the flip angle varies out of the “accurate” band of angles. While 2D acquisitions may obtain accurate T₁ values under limited circumstances, the method examined in this study is not robust enough for practical use. Unless a better flip angle correction or slice profile correction method is used, these results demonstrate that accurate measurements of T₁ are more likely obtained by a thin slab 3D VFA acquisition than from multiple-slice 2D acquisitions.

CONFLICTS OF INTEREST

The authors have no relevant conflicts of interest to disclose.

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SUPPORTING INFORMATION

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Fig. S1. Experimental calculations of T₁ for every combination of flip angles without flip angle correction displayed as percent of true T₁. (a–c) T₁ = 295 ms and (d–f) T₁ = 1045 ms. (a, d) TBP 2, (b, e) TBP 6, (c, f) TBP 10.

Fig. S2. Experimental calculations of T₁ for every combination of flip angles using flip angle correction displayed as percent of true T₁. (a–c) T₁ = 295 ms and (d–f) T₁ = 1045 ms. (a, d) TBP 2, (b, e) TBP 6, (c, f) TBP 10. Flip angles shown are the prescribed flip angle.

Fig. S3. Normalized standard deviation of T₁ [σ_{norm} from Eq. (10)] from experimental data for every combination of flip angles using flip angle correction. (a–c) T₁ = 295 ms and (d–f) T₁ = 1045 ms. (a, d) TBP 2, (b, e) TBP 6, (c, f) TBP 10. Flip angles shown are the prescribed flip angle.

Fig. S4. Simulated accuracy of T₁ using a 2D acquisition in the presence of noise for every combination of flip angles displayed as percent of true T₁. Noise added to give SNR of 10 at Ernst angle. (a–c) T₁ = 295 ms and (d–f) T₁ = 1045 ms. (a, d) TBP 2, (b, e) TBP 6, (c, f) TBP 10. Flip angles shown are the prescribed flip angle. The white lines outline the flip angle combinations that produce T₁ values within $\pm 5\%$ of the true value.

Data S1. The effect of 2D excitation profile on T₁ measurement accuracy using the variable flip angle method.