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Rapid B_1 Mapping Using Orthogonal, Equal-Amplitude RF Pulses

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Abstract

We present a new phase-based method for mapping the amplitude of the radio-frequency (RF) field (B_1) of a transmitter coil in 3-dimension. This method exploits the non-commutation relation between rotations about orthogonal axes. Our implementation of this principle in the current work results in a simple relation between the phase of the final magnetization and the flip angle. In this study we focus on flip angles less than 90° . Compared to the existing B_1 mapping schemes, our method is rapid and easy to implement. The mapping sequence can be simply obtained by adding to a regular 3D gradient-echo (GE) sequence a magnetization preparation RF pulse of the same flip angle but orthogonal in phase to the excitation RF pulse. This method is demonstrated capable of generating reliable maps of the B_1 field within one minute using flip angles no larger than 60° . We show that it is robust against T_1 , small chemical shift and mild background inhomogeneity. This method may especially be suitable for B_1 mapping in situations (e.g., long- T_1 , hyperpolarized-gas imaging, etc.) where magnitude-based methods are not readily applicable. A noise calculation of the flip angle map using this method is also presented.

Keywords

B_1 mapping; RF calibration; flip angle; non-commutation relation; phase sensitive

Introduction

Knowledge of the magnetization flip angle (FA) induced by a radio-frequency (RF) pulse is not only crucial to accurately determine important physiological parameters (1), but essential in MR signal (2) and image (3) optimization. For a hard, on-resonance RF pulse, the FA α at each spatial location is completely determined by the strength of the local rotating magnetic field B_1 via the relation

$$\alpha = \gamma B_1 t, \quad [1]$$

where γ is the gyromagnetic ratio of the nucleus under study, and t is the duration of the RF pulse. The various B_1 mapping methods that have been proposed to date can be broadly

classified as magnitude based (4–11) or phase based (12–17), depending on whether the MR signal magnitude or phase is used in calculation of the FAs and consequently the B_1 strengths.

Different B_1 mapping methods have their strengths and limitations under given circumstances. In general, for example, the commonly used magnitude-based methods (4,5) compute B_1 by comparing signal magnitudes at two different FAs (“double-angle”). These methods therefore require repetition time (TR) to be much longer than the longitudinal relaxation time (T_1), even at small FAs, to allow full magnetization relaxation and to ensure consistent signal magnitude at a given FA. Thus, although these methods have traditionally been used to reliably measure B_1 strength, they generally require long acquisition times. Variations in this category without the long-TR requirement alternatively need the establishment of steady state in a pulse train (11) or high FAs (8), which increases the specific absorption rate (SAR). In addition, these magnitude-based methods are not readily used for hyperpolarized (HP)-gas MR, where the ever-decreasing magnetization, due to T_1 relaxation and RF consumption, results in signal magnitudes that cannot be easily related to the FAs (14,18).

Compared to the magnitude-based methods, the B_1 mapping methods based on signal phase are developing more rapidly in recent years. The schemes that have been used to generate the flip-angle-dependent phase shift include the 2α - α RF pair (12,13), the adiabatic hyperbolic secant pulses (15), and the Bloch-Siegert shift (16). The 2α - α method was shown to yield reliable results for $\alpha \approx 90^\circ$. The high FAs, on the other hand, just as in the magnitude-based methods, require long TR to allow relaxation. The Bloch-Siegert-shift method, recently developed by Sacolick et al. (16), calculates B_1 using the phase shift accumulated during an off-resonance RF pulse. This method was capable of rapid B_1 mapping and in particular was shown to be robust in a variety of situations with different T_1 , chemical shift, field inhomogeneity, and FAs. However, the long, off-resonance RF pulses required to generate the Bloch-Siegert shift not only significantly increase SAR, but also limit the results to maps of off-resonance B_1 field.

In this work we propose another phase-based B_1 mapping method which can be a complement to the existing methods. Compared to the available B_1 mapping schemes, this method is simple to implement and rapid: It only requires one additional magnetization preparation (MP) RF pulse of the same FA but orthogonal to the excitation RF pulse in a regular 3D gradient-echo (GE) imaging sequence; a full 3D B_1 map can be reliably obtained within one minute with FAs no larger than 60° . The FA at each pixel is calculated using the phase deviation of the final magnetization from $\theta = \pi/4$. This method is demonstrated in calculation to be independent to T_1 , small chemical shift, and mild background field inhomogeneity. It can be used as a quick evaluation of the transmitter performance, especially when the magnitude-based methods are not suitable. We call this new B_1 mapping method *orthogonal- α* .

Theory

Assuming the initial magnetization is along $\hat{z}$, i.e., $M_0 = (0,0,1)^T$, consider an α rotation about $-x$ followed by another α rotation about x , as illustrated in Fig. 1, denoted by $R_{-x}(\alpha)$ and $R_y(\alpha)$, respectively. Let τ denote the time interval between the centers of $R_{-x}(\alpha)$ and $R_y(\alpha)$, and $T(\phi)$ the time-evolution operator under free precession and T_2^* relaxation:

$$T(\phi) = \begin{pmatrix} E_2^* \cos \phi & -E_2^* \sin \phi & 0 \\ E_2^* \sin \phi & E_2^* \cos \phi & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad [2]$$

where E_2^* and ϕ denote signal decay due to T_2^* and off-resonance (B_{off}) phase shift between the RF pulses, respectively:

$$E_2^* = \exp(-\tau/T_2^*), \quad \phi = \gamma B_{\text{off}} \tau. \quad [3]$$

The magnetization following $R_{-x}(\alpha)$ and $R_y(\alpha)$ can be calculated as

$$\begin{aligned} & R_y(\alpha) T(\phi) R_{-x}(\alpha) M_0 \\ &= \begin{pmatrix} \cos \alpha & 0 & \sin \alpha \\ 0 & 1 & 0 \\ -\sin \alpha & 0 & \cos \alpha \end{pmatrix} \begin{pmatrix} E_2^* \cos \phi & -E_2^* \sin \phi & 0 \\ E_2^* \sin \phi & E_2^* \cos \phi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & \sin \alpha \\ 0 & -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \\ &= \begin{pmatrix} (1 - E_2^* \sin \phi) \sin \alpha \cos \alpha \\ E_2^* \cos \phi \sin \alpha \\ E_2^* \sin \phi \sin^2 \alpha + \cos^2 \alpha \end{pmatrix}. \end{aligned} \quad [4]$$

If θ_1 is the phase of the resulting magnetization, then

$$\tan \theta_1 = \frac{E_2^* \cos \phi}{(1 - E_2^* \sin \phi) \cos \alpha}. \quad [5]$$

In order to correct for phase accrued between the 2nd RF pulse and echo (TE) due to background field inhomogeneity, a second image set was acquired with the two RF pulses swapped:

$$\begin{aligned} & R_{-x}(\alpha) T(\phi) R_y(\alpha) M_0 \\ &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & \sin \alpha \\ 0 & -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} E_2^* \cos \phi & -E_2^* \sin \phi & 0 \\ E_2^* \sin \phi & E_2^* \cos \phi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \alpha & 0 & \sin \alpha \\ 0 & 1 & 0 \\ -\sin \alpha & 0 & \cos \alpha \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \\ &= \begin{pmatrix} E_2^* \cos \phi \sin \alpha \\ (1 + E_2^* \sin \phi) \sin \alpha \cos \alpha \\ -E_2^* \sin \phi \sin^2 \alpha + \cos^2 \alpha \end{pmatrix}. \end{aligned} \quad [6]$$

Let θ_2 denote the final phase in this situation, then

$$\tan\theta_2 = \frac{(1+E_2^*\sin\phi)\cos\alpha}{E_2^*\cos\phi}. \quad [7]$$

θ_1 and θ_2 as functions of α at different phase shifts ϕ , assuming $E_2^* = 1$, are plotted in Fig. 2. Taking the ratio of Eqs. [7] and [5],

$$\frac{\tan\theta_2}{\tan\theta_1} = \frac{(E_2^*)^{-2} - \sin^2\phi}{\cos^2\phi} \cos^2\alpha = \frac{e^{2\tau/T_2^*} - \sin^2\phi}{\cos^2\phi} \cos^2\alpha. \quad [8]$$

The RF separation τ can be made small by using short RF pulses. When τ is small compared to T_2^* , i.e., $\tau \ll T_2^*$, $e^{2\tau/T_2^*} \approx 1$, the above equation can be simplified and we arrive at the simple relation

$$\frac{\tan\theta_2}{\tan\theta_1} \approx \cos^2\alpha. \quad [9]$$

The FA α can be calculated by

$$\alpha \approx \arccos \sqrt{\tan\theta_2/\tan\theta_1}. \quad [10]$$

Noise Estimation

The noise of the FA map, and therefore the final B_1 map, can be estimated in terms of the signal-to-noise ratio (SNR) of the magnitude image and the corresponding FA. We follow the approach first presented by Conturo et al. (19). For simplicity we only consider the situation where $\phi = 0$ and $\tau \ll T_2^*$. In this case $\tan\theta_1 = 1/\cos\alpha$ and $\tan\theta_2 = \cos\alpha$. We first calculate the variation of $\cos^2\alpha$. Let $A = \cos^2\alpha = \tan\theta_2/\tan\theta_1$, then

$$\sigma^2(A) = \left(\frac{\partial A}{\partial \theta_1}\right)^2 \sigma^2(\theta_1) + \left(\frac{\partial A}{\partial \theta_2}\right)^2 \sigma^2(\theta_2) = \left(\frac{\tan^2\theta_2}{\sin^4\theta_1} + \frac{1}{\tan^2\theta_1 \cos^4\theta_2}\right) \sigma^2(\theta) = 2\cos^2\alpha(1+\cos^2\alpha)^2 \sigma^2(\theta),$$

where we have used $\sin^2\theta_1 = \cos^2\theta_2 = 1/(1+\cos^2\alpha)$ and, since θ_1 and θ_2 are measured separately with the same SNR, their variations are assumed to be uncorrelated and equal, i.e., $\sigma(\theta_1) = \sigma(\theta_2) = \sigma(\theta)$. Using $\sigma(\theta) = \sigma(|I|)/|I|$ (19), we have

$$\sigma(\alpha) = \left|\frac{\partial \alpha}{\partial A}\right| \sigma(A) = \frac{\sqrt{2}}{2} \frac{1+\cos^2\alpha}{\sin\alpha} \frac{\sigma(|I|)}{|I|}. \quad [11]$$

Therefore, the standard deviation (in radian) of the FA map within a region of uniform B_1 is linear with the noise-to-signal ratio (1/SNR) of the magnitude image via the function

$$f_{\text{OA}}(\alpha) = \frac{\sqrt{2}}{2} \frac{1 + \cos^2 \alpha}{\sin \alpha}, \quad [12]$$

where “OA” stands for orthogonal- α .

Materials and Methods

All experiments were performed on a 4.7 T Oxford superconducting magnet driven by the Varian/Agilent UNITY-INOVA console. The magnet has a bore of 12 cm in diameter. The proton resonance frequency is 199.30 MHz. A commercial quadrature birdcage coil (Doty Scientific; diameter = 7.5 cm, length $\approx$ 15 cm) was used for both transmitting and receiving. The phantom was a 100 cc water sphere doped with copper sulfate. Its T_1 was measured to be 0.19 ± 0.01 s using inversion-recovery.

The imaging sequence was a modified 3D GE sequence with a MP RF pulse added at the beginning, as shown in Fig. 3. The MP pulse is orthogonal in phase to but otherwise the same as the excitation RF pulse. The RF pulses are square shaped with the same duration of 80 μ s. A delay of 4 μ s was used between the two pulses, giving an inter-RF separation τ of 84 μ s. In order to eliminate undesired phase accumulation caused by field inhomogeneity (as explained in Theory section), in practice a second image set was acquired with the two RF pulses exchanged. Two α values at 30° and 60° were used; each with 1 and 4 averages. Other sequence parameters include: FOV = 64×64×64 mm³, matrix size = 64×64×64, TR/TE = 5/1.01 ms, imaging bandwidth = 208.3 kHz.

In post-processing, let θ_1' and θ_2' be the original phases of the positive- and negative-phase images, respectively. Under the assumptions of short τ and small φ , from Eqs. [5] and [7], $\tan \theta_1' \tan \theta_2' \approx 1$, i.e., θ_1' and θ_2' are symmetric about $\theta = \pi/4$. To remove any phase shift accumulated during TE, θ_1 and θ_2 at each imaging voxel can be approximated using the difference between θ_1' and θ_2' :

$$\theta_1 = \frac{\pi}{4} + \frac{\theta_1' - \theta_2'}{2}, \quad \theta_2 = \frac{\pi}{4} + \frac{\theta_2' - \theta_1'}{2}. \quad [13]$$

Then the FA was calculated using Eq. [10] on a voxel-by-voxel basis. Errors introduced by this approximation for non-zero φ are estimated in Discussion (Fig. 6).

In order to validate the results of the orthogonal- α method, 2D FA maps were obtained using the magnitude-based, double-angle method with α - 3α implementation (based on the α - 2α method in (5) but with the second pulse replaced by 3α). Let S_α and $S_{3\alpha}$ denote the respective signal magnitudes, the FA at each pixel can be estimated using the relation

$$\sin \alpha = \frac{1}{2} \sqrt{3 - \frac{S_{3\alpha}}{S_\alpha}}. \quad [14]$$

Results

An estimation of the B_1 strength was first made by determining the single-voxel (bulk) null signal from a π nutation. For easy comparison, all B_1 calculations are normalized to values at 50 dBm transmitter power (100 W) in the following text. The result of our initial estimation (π nutation = 40 dBm square pulse at 730 μ s duration) indicated a B_1 strength of 50.9 μ T (1 μ T = 1×10^{-2} Gauss = 1×10^{-6} Tesla) at 50 dBm. This value was used by the spectrometer in the subsequent experiments to compute the desired transmitter power at a given FA.

Figure 4 compares flip-angle maps obtained using the double-angle method and the orthogonal- α method. Figures 4(a) and (d) were acquired using a 2D GE sequence with the α -3 α scheme, where $\alpha \approx 30^\circ$. Figures 4(b), (c), (e) and (f) were obtained using the orthogonal- α method, where $\alpha \approx 30^\circ$ (43.64 dBm) for (b) and (e), and $\alpha \approx 60^\circ$ (49.66 dBm) for (c) and (f). Images (e) and (f) are horizontal (coronal) views of (b) and (c), respectively. 4 averages were used to boost SNR in both image sets, each of which took less than 3 minutes to acquire.

Figure 5 presents B_1 maps obtained using the orthogonal- α method at different FAs and averages. In Figs. 5(a) and (b), $\alpha \approx 30^\circ$; in Figs. 5(c) and (d), $\alpha \approx 60^\circ$. One average was used in Figs. 5(a) and (c), and 4 averages were used in (b) and (d). To quantitatively compare the results, a region of 8 $\times$ 8 which appears to be uniform in Fig. 4 was chosen, as shown in the boxed area in Fig. 5(a). The average values of B_1 in this region are, for Figs. 5(a), (b), (c) and (d), respectively, 53 ± 12 , 52.0 ± 5.4 , 48.5 ± 2.2 , and 47.8 ± 0.9 μ T. For comparison, the average B_1 in the same region from the magnitude-based, α -3 α method (Fig. 4(a)) is 49.7 ± 0.3 μ T.

In order to verify the validity of Eq. [11], FA variation within the boxed region of the FA map (now shown) corresponding to Fig. 5(a) was estimated using Eq. [11] and the SNR's of the magnitude images ($|I| = 6.45$, $\sigma(|I|) = 0.35$ for the positive image; $|I| = 6.33$, $\sigma(|I|) = 0.30$ for the negative image). The calculated value, 0.126, agrees with the FA variation measured directly from the FA map, 0.124 (radian). Estimated and directly measured FA variations in the same region of all FA maps (partly shown in Fig. 4) corresponding to Fig. 5 are listed in Table 1 in Appendix, which demonstrates the validity of Eq. [11] for noise estimation in a FA map obtained using orthogonal- α .

Discussion

The proposed orthogonal- α method provides a simple, rapid, and reliable means to map the B_1 field in 3D. The B_1 strength at each voxel is calculated by measuring the phase of the MR signal following two orthogonal RF pulses. As indicated by Eq. [11], at a given SNR of the magnitude image, the accuracy of FA measurement is positively related to the FA α itself ($\alpha < 90^\circ$). This effect can be seen by comparing Fig. 5(a) and (c): Although the original magnitude images have similar SNR, Fig. 5(c) acquired with $\alpha \approx 60^\circ$ is much more uniform than Fig. 5(a) acquired with $\alpha \approx 30^\circ$. Equation [11] also predicts that at a given FA, accuracy is linear with the magnitude image SNR, which can be easily verified by

comparing the results from Figs. 5(a) and (b), (c) and (d)., Orthogonal- α is rapid: Figs. 5(b), (d) took less than 3 minutes with four acquisitions. In comparison, a similar 3D B_1 map from the magnitude-based, α -3 α method with $TR = 2T_1$ (≈ 0.4 s) would take roughly 40 minutes to acquire because of the need to wait several T_1 between acquisitions. In examining the B_1 results, we noticed a small ($\sim 8\%$) difference in average B_1 strengths measured using $\alpha \approx 30^\circ$ and $\alpha \approx 60^\circ$. This difference is tentatively attributed to system inconsistency in power output but will be a subject of further investigation.

Essentially, orthogonal- α makes use of the fact that in general, two rotations not in the same direction do not commute, i.e., in our case, $R_{-x}(\alpha)R_y(\alpha) \neq R_y(\alpha)R_{-x}(\alpha)$. This non-commutativity is responsible for the phase deviation of the final magnetization from the “central phase”, i.e., $\theta = \pi/4$ in this study. We note that the phase-sensitive, 2α - α method developed by Morrell, et al. (12,13) and the composite-RF approach by Mugler III et al. (14,20) for HP-gas MR are based on the same principle. Compared to the 2α - α method, by switching the two RF pulses in the second acquisition, the treatment for off-resonance is much simplified and its effect is largely removed for mild field inhomogeneity under the condition $\tau \ll T_2^*$. Further, by using a smaller preparation RF pulse, orthogonal- α not only allows faster acquisition but also reduces SAR.

One error of the orthogonal- α method comes from finite T_2^* . The first order Taylor expansion of Eq. [8] reads

$$\frac{\tan\theta_2}{\tan\theta_1} = \frac{e^{2\tau/T_2^*} - \sin^2\phi}{\cos^2\phi} \cos^2\alpha = \left(1 + \frac{2\tau/T_2^*}{\cos^2\phi}\right) \cos^2\alpha. \quad [15]$$

When the condition $\tau \ll T_2^*$ is not satisfied, α will be over estimated. This over estimation will become more evident as ϕ approaches $\pi/2$. In clinical studies the RF pulses are much longer. If we let $\tau = 1$ ms, then $\phi = \pi/2$ corresponds to an off-resonance frequency of 250 Hz, i.e., “banding” errors will appear in the B_1 map at this frequency. Another error, also related to the off-resonance phase shift ϕ , is due to the approximation used in computing θ_1 and θ_2 (Eq. [13]). In Eq. [13], θ_1 and θ_2 are assumed to be symmetric about $\theta = \pi/4$. However, a closer look at the expressions [5] and [7] reveals $\theta_1 - \pi/4 > \pi/4 - \theta_2$ ($\theta_1 - \pi/4 < \pi/4 - \theta_2$) for $\phi > 0$ ($\phi < 0$). The error introduced into the calculation of α by this approximation can be estimated by plugging different ϕ shifts into Eqs. [5] and [7] for a given α , as shown in Fig. 6 for $\alpha = 30^\circ$ and 60° . Under the assumption that the RF bandwidth is large enough to uniformly cover the frequency range over the sample, the plots demonstrate that the approximation used in [11] is robust against small off-resonance phase shift — a $\phi = \pi/6$ shift introduces 7% under-estimation for $\alpha = 30^\circ$ (28°) and 5% under-estimation for $\alpha = 60^\circ$ (57°). In the presence of strong field inhomogeneity, however, Eq. [13] will introduce higher errors and it is no longer a valid approximation. A simple solution in this situation is to introduce a third image with a single RF pulse, which can be used to accurately determine θ_1 and θ_2 . This approach will largely remove the off-resonance-related errors provided $\tau \ll T_2^*$.

Since orthogonal- α is phase sensitive and permits small FAs, a potentially unique application of this method is B_1 mapping in HP-gas MRI, where the MR signals are greatly enhanced due to the highly polarized nuclear spins (21,22). The high FA sensitivity ($f_{OA}(\alpha)$) to magnitude-image SNR at small FAs, therefore, could be compensated by the strong HP-gas signals. For example, let $\alpha = 15^\circ$, then $f_{OA}(\alpha) = 5.28$. In order to have $\sigma(\alpha) < 1^\circ$, the magnitude-image SNR needs to be 300 or higher. We note that images with SNR > 100 are routinely achievable in HP-gas MRI at fine resolutions (21,22). Even higher SNR can be obtained with projection image (i.e., thick slice and no phase-encoding in the third direction) and bigger voxels, which can also avoid early saturation of the available magnetization. It is thus possible to obtain a reasonable projection FA map in HP-gas MRI with only a single bolus of gas using orthogonal- α .

Conclusions

We have demonstrated the feasibility of a new phase-based B_1 mapping method. This method exploits the non-commutation relation of two rotations about axes orthogonal to each other. It computes the flip angles from the phase deviation of the final magnetization from $\pi/4$. It is simple and rapid: Based on a regular 3D GE sequence, it only requires an additional magnetization preparation pulse to implement; a full 3D map of the B_1 field can be generated within one minute. This method can be of particular use in situations such as hyperpolarized-gas MRI where magnitude-based methods are not readily applied.

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Appendix

Table 1

Calculated ($f_{OA}(\alpha)/SNR$, Eq. [11]) and directly measured ($\sigma(\alpha)$) FA variations in images corresponding to the maps in Fig. 5. SNR is calculated in the same boxed region in Fig. 5 using both positive and negative magnitude images. $|I|$ is the average magnitude; $\sigma(|I|)$ is the standard deviation of $|I|$; $f_{OA}(\alpha)$ is defined in Eq. [12].

α	30°				60°			
acquisitions	1		4		1		4	
	positive	negative	positive	negative	positive	negative	positive	negative
$ I $	6.45	6.33	25.45	25.70	7.32	7.38	29.23	29.49
$\sigma(I)$	0.35	0.30	0.68	0.69	0.34	0.32	0.72	0.72
1/SNR	0.051		0.027		0.045		0.025	
$f_{OA}(\alpha)$	2.475				1.021			

α	30°				60°			
acquisitions	1		4		1		4	
	positive	negative	positive	negative	positive	negative	positive	negative
$f_{OA}(\alpha)/\text{SNR}$	0.126		0.066		0.046		0.025	
$\sigma(\alpha)$ (rad)	0.124		0.056		0.045		0.019

FIGURE 1.

Illustration of the two-step rotation processes in the orthogonal- α method. The phase (θ) of the final magnetization after an α rotation about $-x$ (a) followed by another α rotation about x (b) is given by the relation $\tan\theta = 1/\cos\alpha$.

FIGURE 2.

Phase angles of the positive (θ_1) and negative (θ_2) images following two orthogonal RF pulses of flip angle α , from Eqs. [5] and [7], respectively, at different phase shifts (ϕ) and assuming $E_2^* = 1$.

FIGURE 3.

The pulse sequence of the orthogonal- α B_1 mapping method is a regular 3D GE sequence with a magnetization preparation (MP) RF pulse added at the beginning (the first pulse). The MP pulse is orthogonal to the excitation RF pulse. This sequence corresponds to the rotation processes shown in Fig. 1. In this work both RF pulses are square shaped with the same duration of 80 μ s. The delay between the two pulses was 4 μ s, giving an inter-RF separation τ of 84 μ s. One direction of phase-encoding (PE) is omitted in the figure. In a real experiment a second image set was acquired with the two RF pulses exchanged in order to eliminate phase accumulation before data acquisition due to field inhomogeneity.

FIGURE 4.

Flip angle maps obtained using different methods and parameters. All images consist of 64×64 matrices and 1 mm^2 resolution. Images (a) and (d) were acquired using the magnitude-based, α - 3α scheme, where $\alpha \approx 30^\circ$; (b), (c), (e), and (f) were acquired using the phase-based, orthogonal- α method, where $\alpha \approx 30^\circ$ for (b) and (e), and $\alpha \approx 60^\circ$ for (c) and (f). Images (e) and (f) are the horizontal views (coronal) of (b) and (c), respectively. Both image sets were from 3D acquisitions of 4 averages, each of them took less than 3 min. In comparison, such a set of 3D B_1 map would take about 40 minutes to acquire using the magnitude-based, α - 3α method (assuming $\text{TR} = 2T_1 \approx 0.4 \text{ s}$). Due to low SNR in the magnitude images and high uncertainty when α is small (Eq. [11]), the region of reduced FA in (d) and (f) is not as clearly seen in (e).

FIGURE 5.

B_1 maps obtained using the orthogonal- α method with different signal-to-noise ratio and α . All images consist of 64×64 matrices and 1 mm^2 resolution. The B_1 values are normalized to the strength at 50 dBm transmitter power input. (a) $\alpha \approx 30^\circ$, 1 average; (b) $\alpha \approx 30^\circ$, 4 averages; (c) $\alpha \approx 60^\circ$, 1 average; (d) $\alpha \approx 60^\circ$, 4 averages. A selected region, shown in (a), was used to calculate the average B_1 strength and the uncertainty. For the same region, B_1 equals, from (a) to (d), respectively, 53 ± 12 , 52.0 ± 5.4 , 48.5 ± 2.2 , and $47.8 \pm 0.9 \mu\text{T}$ ($1 \mu\text{T} = 1 \times 10^{-2} \text{ Gauss} = 1 \times 10^{-6} \text{ Tesla}$). For the B_1 map using the magnitude-based method (not shown), $B_1 = 49.7 \pm 0.3 \mu\text{T}$. The result from the entire sample (no spatial encoding) is $50.9 \mu\text{T}$.

FIGURE 6.

The calculated flip angles using the approximation [11] when the actual flip angles are 30° (blue) and 60° (red). The difference is caused by the off-resonance phase shift φ . When $\varphi = \pi/6$, assuming RF bandwidth is large enough to uniformly cover the frequency range over sample region, the calculated flip angles are 28.0° and 57.1° for $\alpha = 30^\circ$ and 60° , respectively.