A new phase-based method for rapid 3D B_1 mapping using double RF pulses

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Introduction The B_1 calibration/mapping methods that have been proposed to date can be broadly classified by whether the signal magnitude or the signal phase is used. The magnitude-based methods (1,2) suffer from T_1-limited, long acquisition times; the phase-based methods available so far all have requirements which may hinder their wide applications in the clinics: the 2*α*-*α* method (3,4) requires high flip angles and therefore long acquisition times; the composite-RF approach (5) uses a series of small flip-angle RF pulses which increase the specific absorption rate (SAR); the method using the Bloch-Siegert shift (6) requires long off-resonance RF pulses and only measures off-resonance B_1 field. We present here a simple phase-based method which requires only an additional on-resonance RF pulse of the same flip angle as the excitation RF pulse. It is easy to implement and robust to the T_1, T_2 relaxation times and imaging parameters such as TR and TE. We call it the *double-α* method.

Theory With the initial magnetization along *z*, i.e., $M_0 = (0,0,1)^T$, the phase *θ* of the final magnetization obtained by a -*α* rotation about *x* followed by an *α* rotation about *y* is *α* dependent:

$$\mathrm{R}_y(\alpha)\mathrm{R}_x(-\alpha)M_0 = \begin{pmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \sin\alpha\cos\alpha \\ \sin\alpha \\ \cos^2\alpha \end{pmatrix}$$

[1]. The two rotations are illustrated in Fig. 1.

From the relation $\tan\theta = M_y / M_x = 1/\cos\alpha$ [2] *α* can be calculated using $\alpha = \cos^{-1}(1/\tan\theta)$ [3].

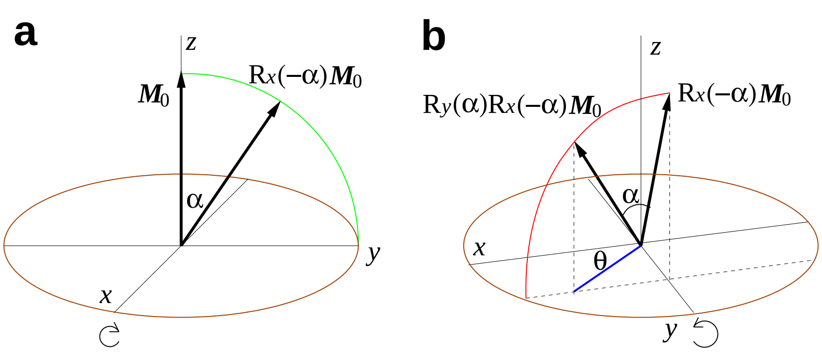

Figure 1 The phase angle *θ* of the final magnetization ($R_y(\alpha)R_x(-\alpha)M_0$) obtained from a -*α* rotation about *x* (**a**) followed an *α* rotation about *y* (**b**) is *α* dependent. *θ* approaches *π*/4 and *π*/2 as *α* approaches 0 and *π*/2, respectively.

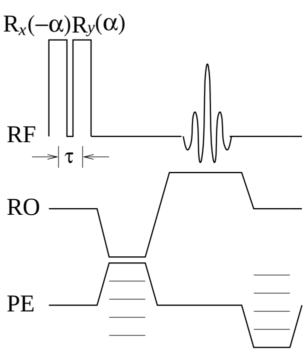

Figure 2 A modified 3D GE imaging sequence with an additional RF pulse was used in our B_1 mapping method.

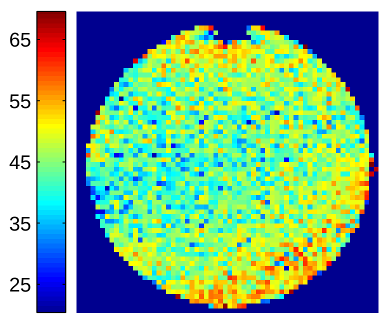

Figure 3 A representative flip angle map obtained using the double-*α* (*α*≈45˚) method. The axis of the low-pass, 8-rung birdcage coil is perpendicular to the image plane.

Methods Experiments were performed on a 4.7 T Oxford superconducting magnet driven by the Varian UNITY-INOVA console. The magnet bore size is 12 cm and the proton resonance frequency is 199.30 MHz. A home-built, low pass quadrature birdcage RF coil of 8 rungs (length: 6.5 cm, diameter: 7.6 cm) was used for both transmitting and receiving. The 100 cc spherical water phantom has a T_1 of 200 ms. A modified 3D gradient-echo (GE) imaging sequence with an additional RF pulse was used for acquisition: the first pulse performs a -*α* rotation about *x* (or *α* rotation about –*x*) and second pulse an *α* rotation about *y*, as shown in Fig. 2. In order to eliminate the off-resonance effect at each pixel, a second image was acquired using the regular single-RF 3D GE sequence. The flip angle can then be calculated from Eq. [3] using the phase difference between the two images at each pixel. Other imaging parameters include: RF width=80 μs (square), inter-RF delay=4 μs, TR/TE=100/1.02 ms, bandwidth=208.3 kHz, FOV=64^3 mm^3, matrix=64^3.

Results A representative flip angle map is show in Fig. 3 for *α*≈45˚. The axis of the coil is perpendicular to the image plane. We see that the B_1 field is uniform for a large region near the center of the coil; in addition, the flip angles in this region are close to the predicted value (45˚) which was estimated using the single-voxel inversion-recovery method. The "hot spots" near the edge of the sphere are caused by the rungs of the coil, as expected. This result demonstrates the feasibility of using the double-*α* scheme as a rapid B_1 mapping method.

Discussion The presented double-*α* approach for B_1 mapping uses essentially the curvature of the unit sphere, which is manifested by the non-commutativity of the rotation operators, e.g., $R_y(\alpha)R_x(-\alpha) \neq R_x(-\alpha)R_y(\alpha)$. Several previously presented B_1 mapping methods (3-5) used the same principle with different implementations. Some other methods make indirect use of this principle by measuring the phase evolution during an off-resonance RF pulse (6,7). In order for better grouping of various B_1 mapping schemes we will refer to any method using off-resonance RF pulses as ***frequency-based*** in future discussions. The double-*α* method has two major sources of errors: 1) the T_2* decay following the first RF pulse reduces the nutation angle (<*α*) of the magnetization before the 2nd RF pulse; 2) magnetizations in regions off resonance (due to B_0 inhomogeneity) are no longer aligned with *y* at the 2nd RF pulse. Both errors can be reduced by using a shorter delay *τ* between the two RF pulses. Our method is most similar to the 2*α*-*α* method (3,4), both of which generate phase deviations using alternating RF pulses in *x* and *y*. However, compared to the latter, the double-*α* method boasts lower SAR due to the smaller flip angle used and therefore shorter acquisition times. The smaller flip angle also reduces second error thanks to the shorter delay (*τ*) between the two pulses, however at the price of a reduced range of *θ* only between *π*/4 and *π*/2. The off-resonance effect was carefully treated in (3). Since *θ* is less sensitive to changes in *α* (Eq. [2]) when *α* is closer to 0, our method is intrinsically noisy in the small-*α* regime. However, in situations where strong magnetization is present, e.g., hyperpolarized gas MR (5), small flip angles can be used and the double-*α* method may be favored over other methods.

Conclusion We have demonstrated a new phase-based B_1 mapping method which is reliable and simple to implement. It uses the phase deviation from *π*/4 of the MR signal following a pair of rotations about the *x* and *y* axes. The method may be particularly suitable for B_1 mapping in hyperpolarized-gas MRI where high flip angles are to be avoided.

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References (1) Hornak JP et al. MRM 1988;6:158 (2) Insko E et al. JMR 1993;103:82 (3) Morrell G et al. ISMRM 1998;2063 (4) Morrell G. MRM 2008;60:889 (5) Mugler III JP et al. ISMRM 2005;789 (6) Sacolick LI et al. MRM 2010;63:1315 (7) Witschey WR et al. ISMRM 2010;2852