Flip Angle Mapping in the Presence of B_0 Inhomogeneity Using Orthogonal-α

Yulin V Chang[1,2], and Philip V Bayly[2]

[1]*Radiology, Washington University, Saint Louis, MO, United States,* [2]*Mechanical Engineering and Materials Science, Washington University, St. Louis, MO, United States*

Introduction Flip angle (FA) or B_1 strength is among the most important parameters in all NMR/MRI/MRS experiments. In addition, FA (B_1^+) mapping is becoming even more important with the rapid development of high-field (HF) (1) and parallel (2) MRI. Among various FA mapping methods, phase-based schemes have in general the advantage of short acquisition times (no need to wait for T_1 recovery or establishment of steady state) and have gained much attention in recent years (3). In particular, a recently proposed method, orthogonal-α, was shown capable of rapid 3D B_1 mapping with moderate FA and robust against small background field (B_0) inhomogeneity (4). The low-FA feature of orthogonal-α makes it of particular interest to HF MRI due to SAR limitations. On the other hand, its applicability at HF remains unclear due to the problem of severe B_0 inhomogeneity commonly associated with HF MRI (5). We investigate in this work the feasibility of FA mapping using orthogonal-α in the presence of strong B_0 inhomogeneity.

Theory To avoid confusion, we briefly re-derive the formulation in the following using row (instead of column) vectors to ensure the same order for the operators and the RF pulses. Let $R_U(\alpha)$ be an α-rotation about the U (x, y, $-x$, or $-y$) axis, $T(\phi)$ and $E_2^* = \exp(-\tau/T_2^*)$ the free precession (of angle ϕ) and the relaxation operators during the inter-pulse delay τ, respectively, then the magnetization following a pair of RF pulse first along y then along –x is

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

. Therefore $\tan\theta_1 = \frac{(1+E_2^*\sin\phi)\cos\alpha}{E_2^*\cos\phi}$, where θ_1 is the phase of the final magnetization; swapping the two RF pulses will result in a new phase θ_2 satisfying $\tan\theta_2 = \frac{E_2^*\cos\phi}{(1-E_2^*\sin\phi)\cos\alpha}$. Since $\frac{\tan\theta_1}{\tan\theta_2} = \frac{\exp(2\tau/T_2^*) - \sin^2\phi}{\cos^2\phi}\cos^2\alpha$ [1], provided $\tau \ll T_2^*$, α can be calculated using $\cos\alpha \approx \sqrt{\tan\theta_1/\tan\theta_2}$ [2].

Methods A home-built 16-rung low-pass birdcage coil (diameter = 8.3 cm, length = 3.8 cm), shown in Fig. 1, was used for FA mapping. The bulk calibration indicated a π nutation at 10 W power input and 700 μs duration for a square pulse (0.75 μT/V). The setup for data collection includes: A 100 cc doped-water spherical phantom (diameter = 5.8 cm); 4.7 T field (resonance frequency = 199.2978716 MHz) from an Oxford superconducting magnet driven by the Varian/Agilent UNITY-INOVA console; the modified gradient-echo (GE) sequence with a magnetization preparation (MP) pulse added at the beginning (4); RF width = 80 μs; target FA = 45°; inter-pulse delay (τ) was varied between 84 and 600 μs; bandwidth = 208.3 kHz; FOV = $(72\ \text{mm})^3$; matrix = 64^3; TR/TE = 5.0/1.02 ms; 16 averages; each single 3D image set took about 5.5 min to acquire; the overall T_2^* at uniform B_0 was about 10 ms; B_0 inhomogeneity was created by skewing the shim gradient in the x-direction; in the presence of B_0 inhomogeneity, a third image set was acquired with a single RF pulse for calculation of θ_1 and θ_2. B_0 map was measured by using an additional GE acquisition with TE increased to 2.04 ms.

Result Figure 2 shows the coronal views of the B_0 maps before and after the field was skewed by the x-shim gradient. Figure 3 displays the FA maps measured under both uniform (a, b) and non-uniform (c-f) B_0, corresponding to the field maps shown in Figs. 2(A) and (B), respectively. In Fig. 3, (a), (c) and (e) are the middle slices of the axial view, (b), (d) and (f) are the corresponding coronal views; (a-d) were acquired with an inter-RF pulse delay of 84 μs, and (e,f) with the delay of 600 μs. The edge enhancement effect for birdcage coil can be clearly seen from the FA maps in the top row of Fig. 3. The regions of low FA shown in the bottom row of Fig. 3 are due to the diminishing B_1 fields at the ends of the coil.

Discussion Taking the result from uniform B_0 shown in Figs. 3(a) and (b) as the standard, we see from Figs. 3(c) and (d) that orthogonal-α produced reliable FA measurement under B_0 inhomogeneity when the inter-pulse delay τ is short compared to T_2^*. However, when τ becomes longer, as shown in Figs. 3(e) and (f), the current implementation of orthogonal-α tend to under estimate FA. This is most likely because when τ is comparable to T_2^*, the approximation $\exp(2\tau/T_2^*)\approx 1$ no longer holds, and the approximation used in Eq. [2] leads to under estimation of α. A possible solution in this situation is to include T_2^* and ϕ in the calculation. Another limitation of the current work is the assumption of infinite wave-lengths generated by the RF coil under study, which is no longer the case in high fields. These two limitations set future directions for further improvements in orthogonal-α.

Figure 1 Pictures of the front (left) and the back (right) of the birdcage coil used for FA mapping in this work.

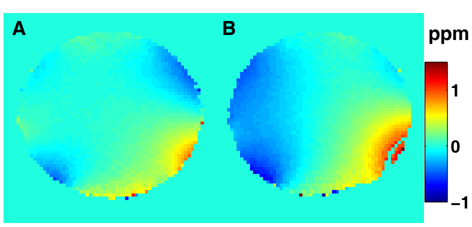

Figure 2 Coronal views of B_0 maps at the 4.7 T field over the sample region before (A) and after (B) being skewed by the x-shim gradient.

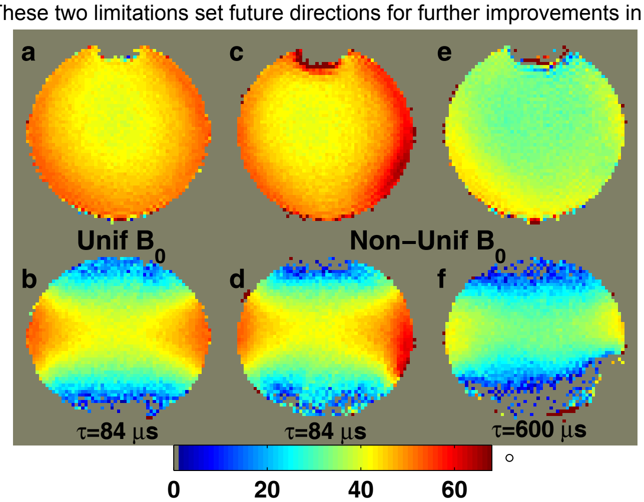

Figure 3 Axial (top row) and coronal (bottom row) views of the FA maps using orthogonal-α under uniform (a,b) and non-uniform (e-f) B_0 fields, with inter-pulse delays (τ) of 84 (a-d) and 600 (e,f) μs. Measurement was not strongly affected by B_0 inhomogeneity provided τ is small compared to T_2^* (comparing (c) and (d) to (a) and (b)); as τ gets longer, however, the approximation used in Eq. [2] leads to under-estimated FA, as shown in (e) and (f).

Conclusions Rapid FA mapping using the current implementation of orthogonal-α in the presence of strong background field inhomogeneity is feasible provided the inter-pulse delay is much shorter than T_2^*. This method is promising for use at high-field MRI. In the situation of long inter-pulse delay, the approximation method leads to under-estimated FA, which we expect to improve by taking T_2^* and ϕ into calculation.

References (1) Setsompop K et al. MRM 2008;59:908 (2) Pruessmann KP et al. MRM 1999;42:952 (3) Sacolick LI et al. MRM 2010;63:1315 (4) Chang VY MRM 10.1002/mrm.23051 (5) Boulant N et al. MRM 2011;65:680

Acknowledgments Work supported by NIH grant R21EB005834.