3D B_1 Mapping for Short T_2^* Spins using Radial Gradient Echo with Gradient Offset Independent Adiabaticity

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Introduction

Obtaining the B_1 map is necessary for a number of MRI methods, including T_1 measurement. Although the actual flip angle method (AFI) [1] is a robust method for B_1 mapping, it is sub-optimal for B_1-mapping in tissues having short T_2^* values due to the relatively long echo-time (TE) of the gradient echo (GRE) sequence normally used in AFI. Although ultra-short T_2* sequences are available, such as UTE[2], ZTE[3] and SWIFT[4], large flip angles are usually difficult to achieve with these methods (due to limited peak RF power and SAR), which significantly reduces the accuracy of AFI for mapping B_1 in ultra-short T_2* imaging. Frequency-modulated (FM) pulses used in SWIFT alleviate this situation to some extent because sequential excitation in space distributes RF energy in time. However, broadband FM pulses still require high power to get sufficient flip angles for AFI. In this study, we introduce a new approach to AFI that achieves 3D B_1 mapping even when T_2^* is short. The approach utilizes <u>CO</u>ncurrent <u>D</u>ephasing and <u>E</u>xcitation (CODE) with <u>G</u>radient <u>O</u>ffset <u>I</u>ndependent <u>A</u>diabaticity (GOIA)[5]. CODE is a short TE radial GRE sequence (TE<500 us) that is relatively robust compared to some other ultra-short TE sequences[6]. The use of GOIA pulses in CODE significantly reduces the peak power and SAR. Here, it is shown that the standard correlation method[7] works well in GOIA-CODE, even when using large flip angles required for AFI.

Theory

Theoretical formalism for the correlation method can be derived from the Bloch equation by applying the low flip angle approximation ($M_z \approx M_0$)[8]. Under the low flip angle approximation, the Bloch equation is analytically integrated and the transverse magnetization, $M_{xy}=M_x+iM_y$, at the end of the pulse duration, T_p, is given by (ignoring transverse relaxation for simplicity):

$$M_{xy}(\mathbf{r},T_p)=i\gamma M_0\int_{-\infty}^{\infty} b_1(\tau)\cdot e^{-i\gamma \mathbf{g}_{ex}\cdot \mathbf{r}(\tau_p-\tau)}d\tau,\quad \mathbf{G}_{ex}(t)=\mathbf{g}_{ex}\cdot m(t),\quad \tau(t)=\int_0^t m(t')dt',\quad b_1(\tau)=B_1(t(\tau))/m(t(\tau)), \qquad [1]$$

where τ is virtual time on the 'time modulated' frame, on which gradient modulation is expressed as time modulation. B_1 and b_1, and $\mathbf{G}_{ex}$ and $\mathbf{g}_{ex}$ represent transverse magnetic fields and excitation gradient vectors on real (t) and virtual (τ) time frames, respectively. $m(t)$ is the gradient modulation function and τ_p is the virtual time at the end of the pulse $\tau(T_p)$.

By using eqs.[1] and ignoring the gradient ramp time, Fourier transformation of the signal acquired in CODE, $\hat{s}(r)$, is given by

$$\hat{s}(r)=i\,|\mathbf{G}_{ro}|^{-1}\cdot \rho(r)\cdot \hat{b}_1(r)\cdot e^{-i\gamma r\tau_p|\mathbf{G}_{ex}|},\quad r=\omega/\gamma\,|\mathbf{G}_{ro}| \qquad [2]$$

in which $\rho(r)$ represents the projection of an object onto the readout gradient vector $\mathbf{G}_{ro}$, and $\hat{b}_1(r)$ is the Fourier transform of $b_1(\tau)$ with respect to τ. Accordingly, $\rho(r)$ is obtained by calculating $\hat{s}(r)/\hat{b}_1(r)$ and then correcting the first order phase.

Method

Validation of the correlation procedure based on eq.[2] was confirmed using a home-built Bloch simulator running on Matlab. Pulse parameters of the GOIA pulse used for simulation and subsequent experiments were as follows: amplitude modulation HS4, gradient modulation HS2, modulation depth 0.5, truncation factor β=5.3, T_p=250 us and bw=80kHz. Transverse magnetization $M_{xy}(r, T_p)$ was simulated for flip angles of 5, 10, 20, 30, and 50°, and then the validity of the correlation process was evaluated by comparing with $\hat{b}_1(r)$. All experiments were performed with a 9.4T 31cm bore scanner (Agilent Technologies Inc.). First, in order to check the gradient modulation effect in GOIA, images were acquired with GOIA and HS1 with flip angles of 4, 20, and 40°. Imaging parameters were common for both cases: TR=4.7 ms, TE=330us, sw=83kHz, 131,072 views, matrix=288x288x288, FOV=64x64x64 mm^3 and scan time=10min 22sec. AFI was performed according to literature[1] by just replacing the imaging segment with GOIA CODE. AFI with 2D GRE was conducted for comparison. We employed TR2=5·TR1 for both cases. Sequence parameters for CODE were TR1=4.5ms, TE=330 us, nominal flip angle=56°, 16,384 views, matrix=128x128x128, FOV=64x64x64mm^3 and scan time 3min 48sec. In gridding in CODE reconstruction, 4 layer view sharing was employed; the innermost layer was composed of views from only one TR dataset (TR1 or TR2) and the number of views from the other TR data gradually increased as the layer shifted to the outer ones. Parameters for 2D GRE were TR1=20ms, TE=1.8ms, 8 slices, slice thickness=2 mm, matrix=128x128, FOV=60x60 mm^2 and scan time 3min 8sec. RF and gradient spoiling were used in both CODE and GRE in order to avoid undesired signals refocusing.

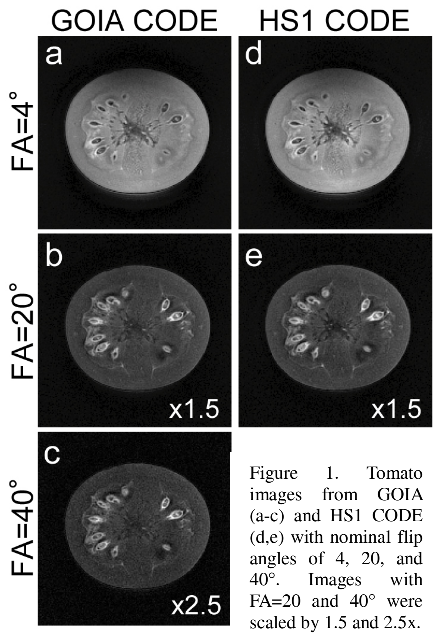

Figure 1. Tomato images from GOIA (a-c) and HS1 CODE (d,e) with nominal flip angles of 4, 20, and 40°. Images with FA=20 and 40° were scaled by 1.5 and 2.5x.

Results and Discussion

The correlation procedure removed the quadratic phase in the excitation profile well regardless of the flip angle; the phase error was less than 5° within the frequency sweep band (80kHz). Change in signal amplitude around the edge of the excitation profile increased slightly as the flip angle increased (~10% for 50°), but the center 60 kHz region within the 80 kHz sweep band showed less than 2% error even for flip angle of 50°, demonstrating the correlation method works well for relatively high flip angles, at least, up to 50° for the pulse used here.

Tomato images acquired by GOIA and HS1 CODE with flip angles of 4, 20 and 40° are shown in Fig.1. Similar image contrast was obtained for both GOIA and HS1, indicating a lack of undesirable effects from gradient modulation (eg, no increase in sensitivity to resonance offset was noted). With HS1, 40° flip angle could not be obtained due to the high peak power required which exceeded the RF power amplifier's capability under the current experimental setting. The peak power and SAR for the GOIA pulse used in this experiment were 40% (~8 dB voltage reduction) and 54% of the HS1 pulse with the same *bw*, T_p, flip angle, and truncation factor. Fig.2 shows TR2 images and actual flip angle maps obtained with AFI using GOIA CODE and 2D GRE. While the reconstructed images showed different contrasts due to different TE and TR, the flip angle maps were consistent with each other. However, 2D GRE failed to capture signals from the central part of tomato because of its relatively long TE and thus showed a noisy region on the flip angle map, but the noisy part did not show up on the map from GOIA CODE.

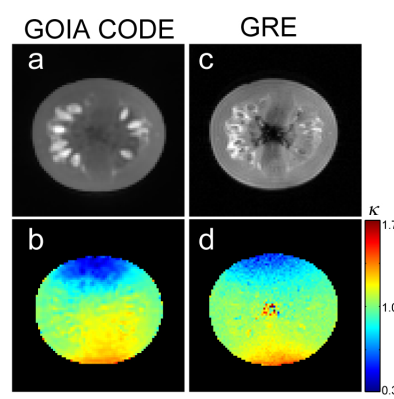

Figure 2. Reconstructed images from TR2 datasets for GOIA CODE (a) and 2D GRE (c), and obtained flip angle scaling, κ, maps from GOIA CODE (b) and GRE (d). Actual flip angles are obtained by κFA. (FA is 56° and 50° for CODE and GRE respectively.)

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