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A modified multi-echo AFI for simultaneous B_1^+ magnitude and phase mapping ☆

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ABSTRACT

To simultaneously acquire the B_1^+ magnitude and B_1^+ phase, a modified multi-echo actual flip-angle imaging (AFI) sequence is proposed. A multi-echo gradient echo sequence was integrated into every even TR of AFI to measure both magnitude and phase of B_1^+. In addition, to increase the signal-to-noise ratio of the B_1^+ phase, a double-angle multi-echo AFI sequence, in which the flip-angle of the RF pulses is α at the odd TR and 2α at the even TR is proposed. Images were simulated to evaluate the performance of this method under various imaging and physical parameters. The performance was compared to the spin echo based B_1^+ mapping method in phantom and in vivo studies.

In the simulation, the estimation error decreased as TR_1/T_1 decreased and TR_2/TR_1 increased. For double-angle AFI, flip-angle ranges that could estimate B_1^+ magnitude and phase better than the original AFI were identified. Using the proposed method, B_1^+ phase estimation was similar to spin echo phase. In the phantom study, correlation coefficient between the estimated B_1^+ phases using the spin echo and the proposed method was 0.9998. The results show that the B_1^+ magnitude and B_1^+ phase can be simultaneously acquired and accurately estimated using the proposed double-angle AFI method.

1. Introduction

Measuring the transmit radio frequency (RF) field, called B_1^+ mapping, can be useful for many MR applications such as determining local RF power [1,2], measuring RF coil performance [3,4], mitigating B_1^+ inhomogeneity using a parallel transmit system [5,6], correcting B_1^+ inhomogeneity effects in various quantitative studies [7–10], and mapping electric property constants [11–15].

While most applications use a measured B_1^+ magnitude map, the B_1^+ phase also holds valuable information for applications such as RF transmit/receive characterization [16,17] and electric property mapping, which require both B_1^+ magnitude and phase information [13,14,18]. In addition to precise B_1^+ magnitude mapping, accurate B_1^+ phase measurements are necessary to calculate electric conductivity [13,18,19].

Several approaches have been developed to map B_1^+ magnitude. A simple method to map the B_1^+ magnitude is the double-angle method (DAM) [20,21], which uses the signal ratios of images acquired using two different flip angles. Alternatives to the DAM use stimulated echoes [22] or the signal nulling method [23]. Other recent advances, such as actual flip-angle imaging (AFI) [24–27], multiple TR B_1/T_1 mapping (MTM) [28], Bloch–Siegart [29], and dual refocusing echo acquisition mode (DREAM) [30], have also been proposed.

One of the commonly used 3D B_1^+ magnitude mapping methods is AFI [24,25], which measures the distribution of flip angles by acquiring data at two different TRs (TR_1 and TR_2). Assuming that the transverse magnetization is completely spoiled and repetition times (TRs) are much shorter than the longitudinal relaxation time ($TR_1 < TR_2 << T_1$), the flip angle (α) can be estimated from two images (S_1 and S_2) measured during the TR_1 and TR_2 intervals, respectively [24].

The MR signal at TE = 0 ideally contains contributions from the B_1^+ and B_1^- phases; however, not all of this information can be acquired. Conventional spin echo (SE) sequences can be used to deduce the TE = 0 phase information while removing the effects of B_0 inhomogeneity. Balanced steady-state free precession (bSSFP) sequences can also provide similar information. The absolute B_1^+ phase is difficult to obtain, and current method seems hard to measure it [15]. For certain coil arrangements or object geometries [14,31,32], the B_1^+ phase is approximately the same as the B_1^- phase ($\angle B_1^+ \angle B_1^-$). Therefore, the B_1^+ phase can be estimated as half of the TE = 0 phase (i.e., half the SE phase). However, simultaneous B_1 magnitude and phase mapping using spin echo requires lengthy scan times to acquire 3D images.

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To simultaneously acquire B_1^+ magnitude and phase, we developed a multi-echo AFI sequence that integrates an AFI sequence with a multi-echo gradient echo sequence to estimate the B_1^+ phase [26,27]. To increase the signal-to-noise ratio (SNR) in the mapping of B_1^+, we propose a double-angle multi-echo AFI (DA AFI) sequence where the flip angle for the multi-echo gradient portion is increased. We performed simulations to observe characteristics of the proposed sequence and determine the optimal flip angles and number of echoes to acquire. The proposed approach was validated with phantom and in vivo experiments.

2. Materials and Methods

We refer to the B_1^+ magnitude estimate as $\hat{B}_{1mag}$, which is the estimated flip angle normalized to the actual flip angle; the B_1^+ phase estimate as $\hat{B}_{1phase}$; the standard deviation of error in the $\hat{B}_{1mag}$ as $\sigma_{\hat{B}_{1mag}}$; and the standard deviation of error in the $\hat{B}_{1phase}$ as $\sigma_{\hat{B}_{1phase}}$.

2.1. Double flip-angle AFI

We combined a multi-echo gradient echo sequence with AFI to acquire the complex B_1^+ map, which includes both magnitude and phase (Fig. 1). The initial gradient echoes (S_1, S_2) were acquired at both TRs (TR_1, TR_2) to calculate $\hat{B}_{1mag}$. Echoes acquired at TR_2 (S_2, S_3, …) were used to calculate $\hat{B}_{1phase}$. The signal intensity acquired at TR_2 determines the precision of $\hat{B}_{1phase}$. In the original AFI sequence, the signal intensity at TR_2 was usually lower than that at TR_1, since longitude magnetization may be less recovered to a steady state if $TR_1 < TR_2 << T_1$. To obtain high signal intensity at TR_2, the flip angles were adjusted such that TR_2 has twice the flip angle of TR_1 (first flip angle, α; second flip angle, 2α). Thus, using a similar approach to [24], the flip angle can be reconstructed by the following closed-form equation.

$$\alpha \approx \cos^{-1}\left(\frac{1-\sqrt{1-2(r-n)r(n-1)}}{2(n-r)}\right), \quad \text{where } r=\frac{S_2}{S_1}, n=\frac{TR_2}{TR} \quad (1)$$

The appendix contains details of the derivation. We assumed that TR_1 and TR_2 are much shorter than the longitudinal relaxation time similar to AFI, therefore, the accuracy of an approximated Eq. (1) is changed under varying TR and relaxation conditions.

We calculated the signal intensities S_1, S_2 based on Eqs. (A.1), (A.2), and (A.3) and computed an intrinsic estimation error in the flip angle estimate using Eq. (1). Fig. 2 illustrates the estimation errors with respect to variation of TR, T_1 relaxation time and the TR ratio (n). Simulations in (a) were performed with TR_1/T_1 ratios of 0.02, 0.06, and 0.2 and $n = 5$ (e.g., TR_2/TR_1: 150/30 ms). These values were chosen with actual T_1 values in mind (1500, 500, and 150 ms). The simulations in (b) were performed with n values of 2, 3, 5, 10, and 15 at $TR_1/T_1 = 0.06$ (e.g., TR_1: 30 ms, T_1: 500 ms). Flip-angle estimates become worse at low flip angles due to noise corruption. The estimation error was less than 8% even TR_1/T_1: 0.5 and n: 5 (Fig. 2(a)), suggesting that the first-order approximation in Eq. (A.4) holds for a broad range of T_1. The TR ratio, n, also affects performance of B_1^+ magnitude mapping (Fig. 2(b)), which is related to the dynamic range of flip-angle variations. Estimation errors less than 5% were achieved as long as n was greater than 3. Increasing n makes the variation in the signal ratio with respect to the flip angle almost linear and also reduces the intrinsic error of Eq. (1). Due to the trade-off in the scan time, the recommended n is in a range of 5–6. Hence, in our implementation, TR_1:TR_2 was set at 30 ms:150 ms, corresponding to $n = 5$.

2.2. Estimation of phase at TE = 0 using multi-echo gradient echo

In a gradient echo based sequence, the phase can be regarded as a sum of the phase produced by RF pulse penetration (φ_0) and a linear accumulation due to B_0 inhomogeneity:

$$\varphi(x,y,z) \cong \varphi_0(x,y,z) - \gamma \Delta B_0 t \quad (2)$$

To determine φ_0 (the initial phase at TE = 0 produced by the RF transmit and receive process), a multi-echo gradient echo sequence was used to remove the effect of B_0 inhomogeneity. From images acquired at multiple TEs, the phase for each pixel can be fitted by most simply using a first-order linear least-squares fitting. The phase mapping equation can be written as:

$$\begin{bmatrix} -\gamma\Delta B_0 \\ \varphi_0 \end{bmatrix} = \begin{bmatrix} TE_1 & 1 \\ TE_2 & 1 \\ \vdots & \vdots \\ TE_N & 1 \end{bmatrix}^+ \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \vdots \\ \varphi_N \end{bmatrix} + \begin{bmatrix} TE_1 & 1 \\ TE_2 & 1 \\ \vdots & \vdots \\ TE_N & 1 \end{bmatrix}^+ \begin{bmatrix} n_{\varphi_1} \\ n_{\varphi_2} \\ \vdots \\ n_{\varphi_N} \end{bmatrix}, \quad (3)$$

$$TE_i = TE_1 + (i-1)\cdot \Delta TE \text{ where } i \geq 2$$

where φ_i represents the phase at TE_i, $^+$ represents a pseudo-inverse of the matrix, and $n_{\varphi i}$ represents a Gaussian distributed noise term for echo i. In bilateral symmetry case, such as a head in a bird cage coil, the B_1^+ phase is half of the transceive phase ($\angle B_1^+ \approx \varphi_0/2$) [14,31,32].

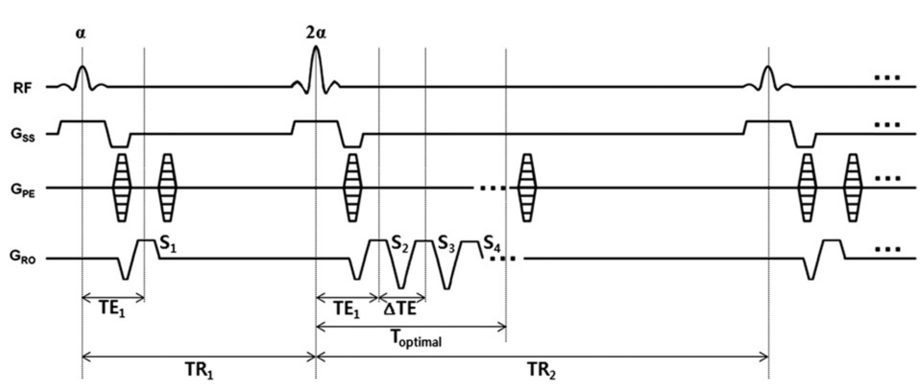

Fig. 1. Pulse sequence diagram of double-angle multi-echo AFI. The RF flip angle of the second pulse was twice the RF flip angle of the first pulse. Multi-echo gradient echoes were acquired during the second pulse. Spoiling gradients were applied on each of the three gradient axes (not shown). The total spoiling gradient area at TR_2 was n ($=TR_2/TR_1$) times the gradient area at TR_1.