Improved T1 mapping with Iterative Actual Flip-angle Imaging (iAFI) Technique

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Introduction: Accurate measurement of T_1 is essential for many quantitative MRI techniques, such as dynamic contrast enhanced MRI. Variable flip angle (VFA) spoiled gradient echo imaging is one of the most widely used methods for T_1 mapping [1]. However, this technique often suffers from flip angle inaccuracies due to inhomogeneous RF fields and slice profile effects [2]. Actual flip-angle imaging (AFI) technique [3] was recently developed to measure the actual flip angle (and equivalently, actual B1) and has been used in conjunction with VFA for improved accuracy [4]. One of the shortcomings of the AFI technique is that the method assumes that T_1 is much longer than the repetition time (TR). When this assumption is violated, large errors can result for both the flip angle and T_1. We propose an iterative AFI (iAFI) method which yields more accurate T_1 values, particularly for relatively short T_1s, and which does not require that TR << T_1.

Theory: In AFI, a gradient echo sequence is used with two interleaved TRs (TR1, TR2, where TR2>TR1) and the same flip angle (α) (Figure 1). Two alternating steady states are achieved and the signal intensity ratio from the two TRs is:

$$r = S_2 / S_1 = \frac{1 - E_1 + (1 - E_2) E_1 \cos\alpha}{1 - E_2 + (1 - E_1) E_2 \cos\alpha} \qquad (1)$$

where $E_{1,2} = \exp(-TR_{1,2} / T_1)$. The actual flip angle can subsequently be calculated:

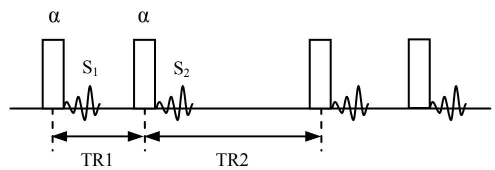

Figure 1. Timing diagram of the AFI pulse sequence

$$\alpha = \arccos\left(\frac{1 - E_1 - r(1 - E_2)}{r(1 - E_1)E_2 - (1 - E_2)E_1}\right) \qquad (2)$$

If TR_1, TR_2 << T_1 is assumed, this expression simplifies to:

$$\alpha \approx \arccos\frac{rn - 1}{n - r} \qquad (3)$$

where $n = TR_2/TR_1$. Equation 3 is independent of T_1. However, as T_1 approaches TR and the assumption is violated, inaccurate flip angles will result. When used in conjunction with VFA for T_1 mapping, erroneous T_1 values will subsequently result.

In the proposed interleaved AFI (iAFI) technique, an initial flip angle is first estimated using the AFI technique using Equation 3 and T_1 estimated using the VFA measurements. The computed T_1 value is then inserted into the AFI model to re-calculate the flip angle map using Equation 2 in which there is no assumption that T_1 is much larger than TR. The new angle is then used to again compute T_1. In this manner, the T_1 and the flip angle are iteratively solved until the differences become negligible.

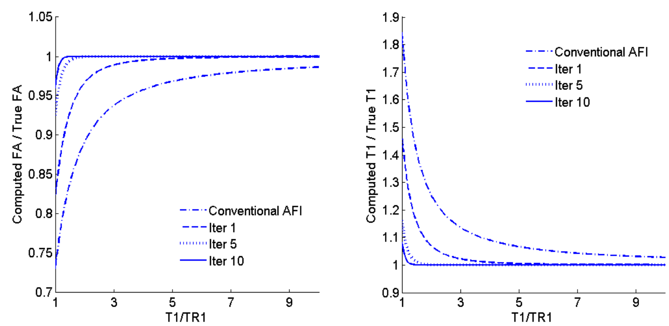

Figure 2. Accuracy of flip angle and T_1 values with iAFI and original AFI

Methods: The accuracy of the proposed iAFI technique was compared to the standard AFI first using simulated data ($TR1/TR2/TR_{VFA}$=30/120/6ms, $\alpha_{AFI}/\alpha_{VFA1}/\alpha_{VFA2}=60^0/4^0/10^0$, T_1 from 30ms~300ms). A phantom experiment was also conducted on a 1.5T Siemens Sonata MR scanner. A gradient echo sequence was used with parameters: $TR1/TR2/TR_{VFA}$=30/120/6ms, $\alpha_{AFI}/\alpha_{VFA1}/\alpha_{VFA2}=60^0/4^0/10^0$ and TE=1.98ms for both AFI and VFA sequences. The phantom contained five tubes with different gadolinium concentrations (0.5, 0.75, 1.0, 1.5, 3.0mM), and the true T_1 values were measured with an inversion-recovery sequence. Typically, less than ten iterations (< 10 sec) were needed for sufficient accuracy.

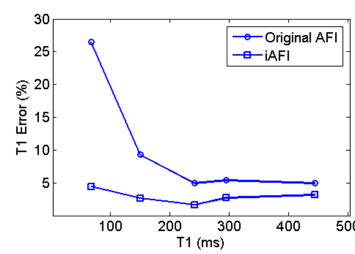

Figure 3. T_1 errors for different T_1s in a phantom study. The actual T_1 values were determined by an inversion recovery experiment.

Results: Figure 2 shows the relative errors of the computed flip angles and T_1s to the true values for different T_1/TR1 ratios in the simulation experiment. Conventional AFI tends to underestimate the actual flip angles and overestimate T_1 values at shorter T_1 values. In contrast, iAFI (after ten iterations) provides a much more accurate estimation of both T_1 and flip angles particularly for small T_1s. Figure 3 shows the T_1 results from the phantom study using both conventional AFI and iAFI techniques. While conventional AFI generates large errors as T_1 decreases, the T_1 errors using iAFI (after 10 iterations) were less than 5% for all T_1 values.

Discussion and Conclusion: We have proposed a method to yield accurate T_1 and flip angle values using iterative AFI. Our results demonstrate that this method provides more accurate T_1 and flip angle values than the conventional AIF technique, particularly for smaller T_1/TR1 ratios, and could potentially be useful for imaging short T_1 species or when longer TRs are used (e.g. to enhance SNR). It was previously reported that T_1 and flip angle maps can be also yielded by solving AFI and VFA equations simultaneously using a single fitting procedure [5], but the accuracy of this method is highly dependent on the initial estimate of T_1 and is much more computationally intensive.

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Reference: ***1.*** Homer et al. J Magn Reson 1985; 63; 287-297. ***2.*** Cheng et al. Magn Reson Med 2006; 55: 566-574. ***3.*** Yarnykh et al. Magn Reson Med 2007; 57:192-200. ***4***. Treier et al. Magn Reson Med 2007; 57: 568-576. ***5.*** Hurley et al. ISMRM 2009; 4450.