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 $T_1$s, 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 ($\alpha$) (Figure 1). Two alternating steady states are achieved and the signal intensity ratio from the two TRs is:

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

(1)

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

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

(2)

If TR1, TR2 $<< T_1$ is assumed, this expression simplifies to:

$$ \alpha \approx \arccos \left( \frac{r-n-1}{n-r} \right) $$

(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.

Methods: The accuracy of the proposed iAFI technique was compared to the standard AFI first using simulated data (TR1/TR2/TRVFA=30/120/6ms, $\alpha_{AFI}/\alpha_{VFA}=60^\circ/4^\circ/10^\circ$). A phantom experiment was also conducted on a 1.5T Siemens Sonata MR scanner. A gradient echo sequence was used with parameters: TR1/TR2/TRVFA=30/120/6ms, $\alpha_{AFI}/\alpha_{VFA}=60^\circ/4^\circ/10^\circ$ 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.

Results: Figure 2 shows the relative errors of the computed flip angles and $T_1$s 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 more much accurate estimation of both $T_1$ and flip angles particularly for small $T_1$s. 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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