Accurate and Efficient Mapping of Flip Angle and T1 using Simultaneous Actual Flip Angle - Variable Flip Angle Imaging (AFI-T1)

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Introduction: The knowledge of flip angle values is essential for accurate modeling in many quantitative MRI techniques. Recently, Actual Flip Angle Imaging (AFI) was proposed to account for multiple sources of flip angle variations such as transmit field inhomogeneity, B0 variations, slab profile, and excitation pulse effects [1]. AFI was successfully applied to yield system-independent T_1 relaxivity maps from variable flip angle (VFA) SPGR measurements [1-4]. AFI assumes the repetition time is much less than T_1. When this assumption is violated, significant errors in flip angle and in subsequent T_1 estimates may arise.

We propose a modification of the AFI technique that simultaneously yields T_1-independent AFI flip angle maps and accurate T_1 values. The new method (AFI-T1) exploits a synergy between AFI and VFA acquisitions, arising from the similarity of the steady state spoiled gradient echo (SPGR) based pulse sequences. AFI-T1 allows for more accurate flip angle mapping over a wide range of T_1 and results in a reduction of total time required for corrected T_1 mapping.

Theory: AFI calculates flip angle using the ratio of two images (S_1, S_2) obtained from two interleaved repetition times (TR_1, TR_2) in a steady state. For TR_1, $TR_2 << T_1$, the T_1 dependence of AFI signals may be ignored in flip angle calculations [1]. In the AFI-T1 method, we do not ignore T_1 dependence but instead utilize it to couple flip angle and T_1 estimation into a single procedure. Both the AFI and VFA T_1 modeling equations share the proton density factor (PD), which is ignored in the original AFI implementation. This redundancy may allow the elimination of one VFA measurement, but cannot be exploited in the standard approach because AFI flip angle calibration precedes VFA T_1 calculation (Fig. 1). To exploit both PD redundancy and T_1 coupling, we have combined T_1 and AFI fitting into a single procedure (AFI-T1) using vector-valued modeling. This approach iteratively minimizes the AFI and VFA modeling equations (Fig. 1) to simultaneously yield flip angle, PD, and T_1 values from AFI and VFA measurements. This avoids the aforementioned pitfalls of separate modeling and can reduce the required number of VFA datasets by one.

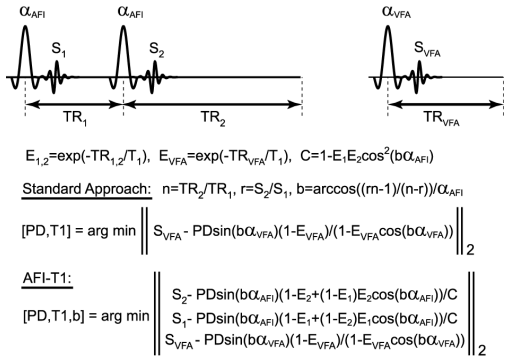

Figure 1: Vector-valued fitting procedures for the standard approach (VFA) and AFI-T1. AFI-T1 combines the AFI and VFA models into a single procedure, accounting for the T_1 dependence of flip angle mapping and shared proton density factor (PD).

Methods and Results: First, we evaluated the performance of the original AFI and proposed AFI-T1 methods at short T_1 times in simulations (Fig. 2). While AFI significantly underestimates flip angle at short T_1, AFI-T1 provides accurate flip angle values for all T_1 times. To investigate noise performance, we ran Monte-Carlo simulations (PD=1, T_1=1s, $TR_1/TR_2/TR_{VFA}$=15/75/15ms, α_{AFI}=60º) (Table 1, Fig. 3). Simulation for a single SPGR showed an optimum $R_1=1/T_1$ precision at α_{SPGR}=5º (TR_1/TR_2=15/75ms) (Fig. 3). A range of α_{SPGR} from 1º to 13º yielded significantly higher noise efficiency than AFI-corrected VFA (by a factor of 1.8), demonstrating a wider flexibility in choice of flip angle for AFI-T1 (Table 1). Simulation for 2 SPGR measurements (not shown) showed an optimum AFI-T1 precision when both flip angles were the same, demonstrating that AFI-T1 performs best with a single SPGR measurement for the given T_1 time.

We also demonstrated AFI-T1 with real data. The AFI-T1 pulse sequences were implemented on a Varian 4.7T small animal MRI (Palo Alto, CA) and validated on ex-vivo fixed rat brains. SPGR measurements were performed using a spoiled 3D gradient echo sequence (TR=15ms, matrix size 64x64x96, α_{SPGR}=[6º 34º]). AFI measurements were performed using a modified double-delay sequence [1] for the same matrix size with a TR_1/TR_2=15ms/75ms, α_{AFI}=60º. We evaluated VFA without AFI correction, VFA with AFI correction (with 2 SPGR measurements), and combined AFI-T1 with a single SPGR measurement (α=6º). A small averaging window was applied to the AFI flip angle maps in all approaches. For AFI-T1, the flip angle map was re-input to a second fit as an independent parameter. AFI-T1 demonstrated improved noise performance over VFA with AFI correction (Fig. 4), even with the reduction of 1 SPGR measurement.

Discussion: We have proposed a method to combine flip angle and T_1 measurements in a single procedure (AFI-T1). This novel AFI-T1 approach avoids the pitfalls of separate AFI and VFA T_1 modeling, such as inaccurate estimation of flip angle and T_1 estimates at shorter T_1 times and redundant data acquisition. Unlike the original AFI procedure, the proposed procedure demonstrates insensitivity to T_1 weighing, and may potentially extend accurate flip angle imaging to a wider range of applications (longer TR in multislab/multislice acquisitions or shorter T_1 in Gd-enhanced tissue or fatty tissues). This comes at the expense of one additional SPGR measurement, which increases scan time by approximately 16%, but at the benefit of additional T_1 and PD maps. Compared to VFA T_1 mapping, the scan time may be reduced by as much as 50%. Additionally, we demonstrated that the combined AFI-T1 fit is more noise efficient than the separate AFI and VFA T_1, allowing greater flexibility in the selection of an SPGR flip angle. The improved noise efficiency, accuracy, and reduction of total scan time are partially due to the use of nonlinear vector-valued modeling, although this procedure is computationally more demanding than the individual VFA and AFI methods.

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References: [1] Yarnykh V. MRM, 2007, 57:192-200. [2] Treier R, et al. MRM, 2007, 57:568-576. [3] Wang HZ, et al. MRM, 1987, 5:399–416. [4] Deoni SCL, et al. MRM, 2003, 49:515–526.

	PD	R1, s^{-1}	Flip°
AFI-corrected VFA (2 SPGR)	1.003 ±.027	0.996 ±.047	59.84 ±.994
AFI-T1 (1 SPGR)	1.000 ±.043	1.000 ±.026	59.97 ±1.01

Table 1: Comparison of fitting accuracy and precision in simulations (R_1=1s^{-1}), PD=1, TR1/TR2=15/75ms) VFA performed at "ideal" flip angles [4º, 24º]; AFI-T1 at α_{SPGR}= 5º.

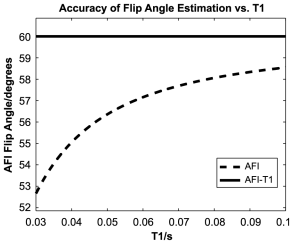

Figure 2: Accuracy of flip angle with standard AFI and new AFI-T1 for shorter T1 (flip angle 60° TR_1/TR_2=15/75 ms).

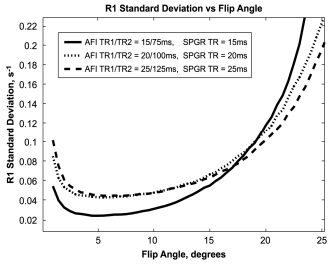

Figure 3: Precision of R1 estimates vs. flip angle of SPGR scan for R1=1 s^{-1}, α_{AFI}=60°. Optimal performance is gained within wide range of flip angles about [3° 10°].

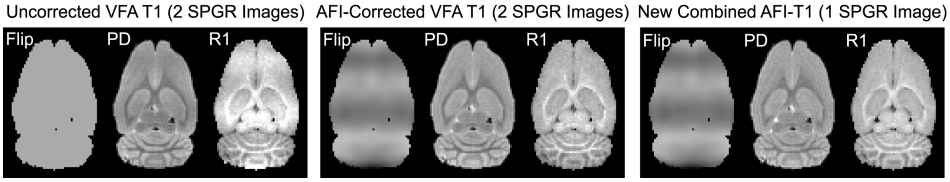

Figure 4. VFA T1 mapping without FA correction results in significant errors in proton density (PD) and R_1 maps. AFI calibration shows FA variations due to B1 inhomogeneity and slab profile. AFI-T1 yielded accurate FA and R1 with 1 less VFA SPGR measurement and improved precision (R1=1.72±-0.112 for VFA, 1.77±0.106 for AFI-T1, in gray matter).