T1 Error Analysis for Double Angle Technique and Comparison to Inversion Recovery b-SSFP Look-Locker Acquisition

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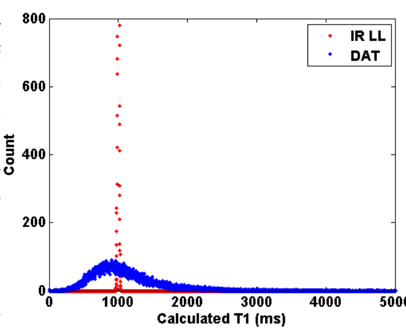
Introduction: The multiple flip angle (MFA) [1] and inversion recovery (IR) based methods are two of the widely used techniques to determine T1 values in vivo. To improve acquisition speed, the dual (two) flip angle technique (DAT) with short repetition times is primarily employed while IR followed by Look-Locker acquisitions is employed with inversion recovery schemes. Typically, absolute quantitative values of T1 should be invariant of the scanner or the site or the scanning technique used. However, the accuracy, reliability and repeatability of measurements can be impacted in several ways. The choice of optimal flip angles to be used with DAT has been studied quite extensively [2, 3]. More recently, the dependence of T1 on RF spoiling was investigated [4]. Here we systematically investigate various sources of error inherent mainly with DAT and compare it with IR based LL b-SSFP [5]. It is shown that the sources of error for DAT can impact the accuracy and variance in T1 values substantially when compared with IR based LL.

Materials and Methods: The solution to DAT is obtained by fitting a line through values of $S_{1,2}/\sin(\alpha_{1,2})$ vs $S_{1,2}/\tan(\alpha_{1,2})$. The T1 value is then obtained as T1= −TR/log(m), where m is the slope of the fitted line. Correction for B1 inhomogeneity is applied based on the method described in [6]. For the results presented here, we assume TR/T1=0.01 unless otherwise noted. This value for TR/T1 is in agreement with values used in literature to derive brain T1 maps where T1~1s and TR used is ~10ms [3]. Optimal $\alpha_{1,2}$ values are calculated based on eq (11) of [3] and are around 4° and 19° for the given TR/T1. *Slope Dependence:* For the values indicated, slope m=0.99. An error of 0.5% in slope determination (from m=0.99 to m=0.995) results in an error in T1 of 90%. An approximate quantitative estimate for σ_{T1} as a function of σ_m (error in slope) can be obtained by performing error propagation analysis which shows that $\sigma_{T1}=\sigma_m TR/m[\log(m)]^2$. Error analysis provides a similar value with σ_m=0.005 resulting in σ_{T1}=500ms. *SNR Dependence*: The effect of SNR variance on T1 was investigated since σ_m is a reflection of σ_S (signal std.) related directly to SNR for the two acquired images. For this purpose, Monte Carlo simulation where Gaussian noise (with μ=0 and $\sigma = 0.01M_0$) was added to $S_{1,2}$ was done. T1 was then calculated based on these values of $S_{1,2}$. The process was repeated 65000 times. The calculated T1 values showed a μ=1009.7ms and σ=226.3ms for DAT. (Note that with TR=1.1T1 as indicated in [2], σ_{T1}=48ms.) A similar exercise for T1 values obtained from three S values (TI=300ms,900ms,1500ms) with the same noise added for the case of inversion recovery gives T1=999.95±10ms. This is also borne out by error analysis (neglecting M_z modulation) which predicts $\sigma_{T1}=\sigma_{M0}T1^2\exp(-t/T1)/2t$ where t is the sampling time (typically TI) on the inversion recovery curve. For TI>210ms, σ_{T1}<20ms. Figure 1 shows the T1 distributions obtained using Monte Carlo simulations for both the DAT and the IR technique. Of importance is the bias towards larger (>1000ms) T1 values for DAT when compared with IR indicating possible systematic error in accuracy of calculated T1 values. *Angle (B1) Dependence*: An equation relating errors in transmitted flip angles to the error in T1 was derived. The equation was tested against Monte Carlo simulations similar to the process described earlier. Accordingly, for a σ_α=0.1 (normalized), σ_{T1}=142.9ms (simulated) and 266ms (calculated). If σ_α=0.05, σ_{T1}=71.4ms (simulated) and 133.01ms (calculated). So an error of 5% in the flip angle results in about a two fold error in the value of T1. *Scanning (repeatability)*: Phantoms with two different T1s (T1~950ms and 2600ms) and seven volunteers were scanned (3T Philips Achieva scanner; release 2.5.3) using the two techniques: (a) DAT acquisition (3DFFE, TR/TE=10/3ms, α_1=4°, α_2=19°, 117° spoiling), 25 slices; B1 correction: 3D FFE, TR1/TR2=25/125ms, 33° spoiling [7] and (b) IR (adiabatic RF pulse) based LL technique, 25 slices [5]. Resolution was kept the same for both DAT and IR; scan time was slightly over 4 mins (including B1mapping sequence) for DAT and was under 2mins for the IR LL technique. Scans were repeated six times and $\sigma^2/\langle T1\rangle$ (variance across six measurements normalized to average T1) was calculated in phantoms and in GM (caudate nucleus) and WM for volunteers. In addition, for two volunteers, scanning was also performed with TR=100ms, α_1=11°, α_2=56° (optimal flip angles) for comparison to the short TR (TR=10ms) case. In one volunteer, the spoiling angle was varied ±2° about 117°.



Results: Table 1 shows values for $\sigma^2/\langle T1\rangle$ for the two phantoms while Table 2 shows values for the average $\sigma^2/\langle T1\rangle$ across seven volunteers. For DAT, the first value in the column reflects values obtained after correction for B1 inhomogeneity while the second value reflects the value prior to correction for B1. For the case when TR=100ms, the uncorrected T1 values were lower by an average of 9.4% (for WM) and 7.9% (for GM) when compared with values obtained with TR=10ms; they were lower by an average of 7.8% (for WM) and 2.1% (for GM) after correction for B1 inhomogeneity. Varying the spoiling angle by ±2° about optimal spoiling angle of 117° resulted in $\sigma^2/\langle T1\rangle$ of 2.43 (WM) and 7.13 (GM) for uncorrected T1 and 3.33 (WM) and 9.16 (GM) with corrected T1 values.

Table 1	IR-LL	DAT (B1 corr/uncorr)
Phantom 1	0.0063	0.017 / 0.079
Phantom 2	0.0015	0.348 / 0.388

Discussion: Several factors affect accuracy of the double flip angle technique including SNR of measurements, accuracy of slope determination (partly dependent on SNR), the two flip angles used, the spoiling angle used in DAT as well as B1 correction sequence, the value of TR/T1 and sensitivity to B1 inhomogeneity. An attempt has been made here through simulations and experiments to understand the relative importance and impact of some of the factors neglected in literature. Of particular interest is the bias towards higher calculated T1 values seen in Monte Carlo simulations of DAT. When TR/T1 was increased from 0.01 to 0.1 and higher, a trend towards lower T1 values was noticed. The gross effect of the various factors gets reflected in the substantially poor reproducibility of the measurements in phantoms and volunteer scans when compared with inversion recovery LL based technique.

Table 2	IR-LL		DAT	
Volunteer scans	WM	GM	WM (corr/uncorr)	GM(corr/uncorr)
Mean($\sigma^2/\langle T1\rangle$)	0.0275	0.109	0.524 / 0.521	2.28 / 2.16

References: [1] Christensen K. *J. Phy. Chem*. 78:1971-1977, 1974. [2] Wang HZ et al. *MRM* 5:399-416, 1987. [3] Deoni S et al. *MRM* 49:515-526, 2003. [4] Yarnykh V. *ISMRM* 2008:234. [5] Gai N. et al. *JMRI* 30:640-648, 2009. [6] Yarnykh V. MRM 57: 190-200, 2007. [7] Yarnykh V. *ISMRM* 2008: 3090.