Improved T1 estimation with spoiled gradient recalled echo (SPGR) images using a modified variable flip angle method

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Introduction: In spoiled gradient recalled echo (SPGR) images, when the echo time *TE* is very short compared to T_2*, the signal from sample *j* (*j*=1, 2, …, n) at measurement *i* (*i*=0, 1, …, m) is expressed as $S_{ij}=M_0 sin(\alpha_i)[1- exp(-TR/T_{1j})]/[(1- exp(-TR/T_{1j})cos(\alpha_i)]$, Eqn.[1], where *TR* is the repetition time, α_i is the flip angle at measurement *i*, M_{0j} is the proton density and T_{1j} is the longitudinal relaxation time for sample *j*. In the traditional variable flip angle method, for each sample *j* its proton density M_{0j} and T_{1j} values are individually estimated by minimizing the sum of squared errors, $SSE_j=\Sigma_{i=1..m}(\hat{S}_{ij}-S_{ij})^2$ Eqn.[2], where $\hat{S}_{ij}$ denotes the measured signal. This method for T_1 measurement is fast when short *TR* is used. However, it is subject to errors caused by imperfect flip angle profiles which can result from non-ideal excitation RF pulse, inhomogeneity in the RF transmit field and inaccurate RF transmitter power (1).

Materials and Methods: The traditional variable flip angle method assumes all the flip angles α_i are known and exactly equal to the prescribed flip angles. In our modified variable flip angle method, we consider α_i as unknown variables and propose to estimate them together with all the M_{0j} and T_{1j} by minimizing the global $SSE=\Sigma_{i=1,..m,\, j=1,...,n}(\hat{S}_{ij}-S_{ij})^2$ Eqn.[3]. There are $m\times n$ measured signals, and totally $i+2n$ unknown variables. It is possible to have a unique solution from the fit when $m\times n \geq i+2n$ Eqn.[4]. This is only possible when at least 3 flip angles are measured. In practice, usually T_{1j}>>*TR* and α_i are small. In this parameter regime even when Eqn.[4] is satisfied, there are an infinite number of solutions due to the scaling property of Eqn.[1]. If a parameter set $\{\alpha_i, T_{1j}\}$ is a solution, then all the parameter sets $\{A\alpha_i, T_{1j}/A^2\}$ in the same parameter regime are also solutions with *A* being any coefficient. To get a unique solution, at least one constraint is needed such as the value of one α_i, M_{0j} or T_{1j}. In the modified method, all the samples can be assumed to have the same effective flip angles which are not necessarily equal to the prescribed ones. This assumption is likely a good approximation in the central region of images acquired with 3D slab excitation. When the flip angle is spatially inhomogeneous due to non-ideal RF pulse and/or inhomogeneous RF transmit field, the true flip angles for sample *j* can be expressed as $B_j\alpha_i$, where B_j only depends on the position of sample *j*. In this case we have theoretically proved that the modified method works the same way except that the apparent T_{1j} values estimated from Eqn.[3] should be divided by B_j^2 to obtain the true T_{1j} values.

A Eurospin phantom, which consists of 11 tubes of copper-doped gel with manufacturer supplied reference T_{1j} values ranging from 221 ms to 992 ms, were scanned with 3D SPGR at TR=3.8 ms and three prescribed flip angles $\alpha_1/\alpha_2/\alpha_3$ =5/13/28° using a brain coil in a Siemens 1.5T Magnetom scanner. For every tube a Volume of Interest (VOI) of the same size was selected from the central slices and the average signal from the VOI was used in our analysis. The adjusted chi-square, defined as the global SSE divided by the degree of freedom of the fit, is used to indicate the goodness of the fit.

Results: Firstly we applied the traditional method to the data. The adjusted Chi-square of the fit is 397.9. Figure 1**a** shows that the residuals of the fit are apparently correlated, which strongly indicates failure of the model likely due to imperfect flip angles. Secondly, to estimate the effective flip angles we entered the reference T_{1j} values of the 11 samples into Eqn.[3]. The adjusted Chi-square of the fit is 42.3 and there is no clear pattern in the residuals (data not shown). The effective flip angles and the 2-sigma errors are estimated to be α_1=4.86± 0.21, α_2=12.28± 0.50, α_3 =30.41± 0.83, which shows that the effective flip angles of α_2 and α_3 are significantly different from their prescribed ones. Finally, notice that the difference between the prescribed α_1 and its effective value is not statistically significant, by only fixing α_1=5 we applied the modified method to estimate the T_{1j} values. The adjusted Chi-square of the fit is reduced to 32.72 and the residuals appear random (Fig. 1**b**). The estimated errors of the fitted T_{1j} were reduced by about 50% compared to the traditional method (Fig. 2). In another data set of the same phantom similarly acquired from a Siemens 1.5T Avanto scanner, we found the effective α_1 was also very close to its prescribed value 5 and the analysis with the modified method assuming α_1=5 produced dramatic improvement in both curve fitting and T_1 estimation as well.

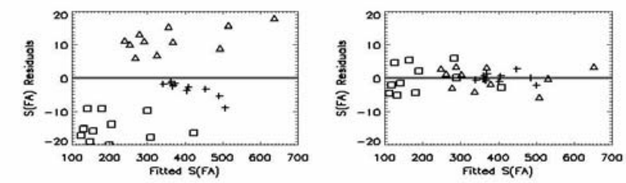

Figure 1. Residuals of the signals plot against fitted signal. (a) Traditional variable angle method. (b) Modified method only assuming α_1=5. The data from flip angles 1, 2, 3 are respectively plotted as plus signs, triangles and rectangles.

Conclusions and Discussions: If the T_1 values of one or more tissues/samples are known, the modified variable angle method can be easily applied to calibrate all the effective flip angles, and simultaneously estimate all the unknown T_1 values if there are any. In clinical applications, it is possible that the small flip angles are usually precise for 3D slab excitation. This information alone can be utilized to provide a more accurate T_1 estimation using the modified variable flip angle method. This method provides a means to find the effective flip angles using phantom data or even in vivo images themselves, hence improve the T_1 estimation.

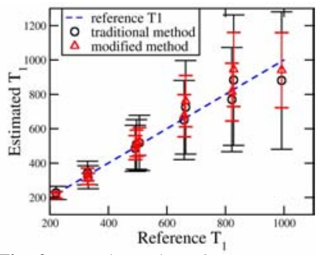

Fig. 2. Error bars show 2σ errors.

References: 1. Brookes JA *et al*, JMRI 9: 163-171 (1999).