Fast Accurate Measurement of T1 Incorporating Flip Angle Calibration and Correction

J. Wang[1], M. Qiu[1], R. T. Constable[1,2]

[1]Department of Diagnostic Radiology, Yale University, New Haven, CT, United States, [2]Department of Biomedical Engineering, Yale University, New Haven, CT, United States

ABSTRACT

A fast and accurate method incorporating flip angle calibration/correction is shown to make the variable flip angle approach for measurement of T1 feasible. In a phantom study, a T1 of 1391 ± 37 ms is estimated by the conventional IR method in 100 minutes, and 1190 ± 340 ms / 1493 ± 33 ms before / after correction with the proposed method in 10 minutes. Highly uniform distributions of T1 in five subjects WM of 900 ± 3 ms, GM of 1337 ± 8 ms CSF of 2180 ± 25 ms were found with an acquisition time of 6 minutes.

INTRODUCTION

The spin-lattice relaxation time T_1 varies between different tissues and may be exploited for differentiating normal and pathological tissues. This potential has led to interest in fast methods for measuring T_1. Conventionally, T_1 can be estimated using magnetization preparation such as saturation-recovery sequences with multiple repetition times (TR), or inversion recovery (IR) sequences with multiple inversion recovery times (TI). At high field, the RF non-uniformity becomes large and has a strong affect on the T_1 measurement. The magnetization preparation approach introduces an inversion RF pulse and suffers primarily from long scan times. At high field the additional problem of RF inhomogeneity becomes an issue. Here we report a new method for accurate T_1, which is based on the variable flip angle (FA) method with the addition of a correction for the effect of non-uniform FA and calibration of the in vivo measured FA as well as prescribed FA for each object imaged. Phantom studies are shown indicating that this approach is effective for measuring T_1. In vivo results are also shown illustrating highly uniform T_1's across subjects for the specific brain tissues. These results indicate that this approach is attractive for practical applications requiring T_1 mapping, particularly at high field.

THEORY

The signal intensity of an ideal spoiled gradient-echo sequence with an excitation flip angle of α can be approximated as [1]

$$SI(x) = M_0 \cdot \sin\alpha \cdot s(x) \cdot \frac{(1-E_1)}{(1-E_1 \cdot \cos\alpha)} \qquad (1)$$

$$T_1 = \frac{-TR}{\ln b} \qquad (2)$$

where M_0 is the equilibrium longitudinal magnetization, s(x) is reception sensitivity and $E_1 = \exp(-\frac{TR}{T_1})$. The T_1 can then be written with Equ. [2].

In practice, due to a non-uniform RF distribution, the actual flip angle α is a function of spatial location. Thus to use this approach, a calibration factor, that describes the difference between the true FA and the prescribed FA, must be obtained to estimate the true FA [2]. For homogeneous signal intensity, the true FA of 90° corresponds to the maximum signal intensity for a free induced decay at the long TR, or the true FA of 180° locates the signal zero crossing. Non-uniformities in the RF across a slice at high field, negatively impact the use of standard 90° and 180° methods for estimating the RF calibration factor, and a variety of other methods have been developed for this task. We proposed a new method by which the calibration factor can be determined by the slope of the measured FA vs. nominal (prescribed) FA curve in the linear region of B_1^+ and FA. The true FA at each pixel then can be scaled accordingly.

METHOD

Phantom and human brain images were acquired on a Siemens 3.0 T Trio system. Two 15 cm diameter cylindrical phantoms, one filled with 1% low fat milk (Deerfield farms) and the other filled with oil, were used to evaluate the proposed method. To illustrate the linear relationship between B_1^+ and the nominal FA, the B_1^+ fields for the different FAs from 20° to 360° were measured using a gradient echo sequence with FA increments of 10°. The acquisition parameters were TR/TE = 8000/4 ms, resolution 1.6x1.6x 5 mm^3. A conventional IR-SE pulse sequence was used to estimate the milk phantom T_1 for reference to evaluate proposed method. Axial images were acquired with resolution 0.8x0.8x5 mm^3 and FA of 90° and an acquisition time of ~ 100 minutes. The transmission field maps of both phantoms were obtained using a segmented SE-EPI sequence with excitation FAs of 60° and 120°, TR/TE 8000/4 ms, resolution 0.8x0.8x5 mm^3. For human studies, the field map was acquired using the segmented SE-EPI with nominal excitation FAs of 30°, 60° and 120°, at TR/TE 1740 /14 ms, resolution 1.6x1.6x 6 mm^3, and 5 shots. The calibration of the FAs can be separately determined based on the assumption of a linear relationship between B_1^+ and the nominal or the measured FA. For the five normal volunteers, the segmented SE-EPI sequence was to measure the B_1^+ map and calibration factor in vivo for each subject, with nominal excitation FA's of 60° and 120°, and refocusing pulses of 120° and 240°. T_1 maps of the five subjects were estimated using two variable FA images acquired with the GE sequence with nominal excitation FA's of 23° and 122° with the flip angle calibration and RF non-uniformity correction.

RESULTS AND DISCUSSION

Fig. 1 shows the dynamic range (DR) of the regression of T1 measurement for different FAs. Taking the DR and SNR over all combinations of FAs yields optimum FAs of 23° and 122° to minimize the error of T_1 measurement. Fig. 2 displays the measured vs nominal FAs over this range of flip angles and illustrates that the linear relationship between measured and nominal FAs holds up to about 260°. The slope of the curves provides RF calibration factors of 0.82 for oil phantom and 0.78 for milk phantom respectively. In comparison with conventional IR method, the proposed method provides a more uniform T1 distribution in less scan time (Fig. 3). The proposed method measured the T_1 of the milk phantom of 1190 ± 340 ms before the RF correction, and 1493 ± 33 ms after the correction using the B_1^+ map.

Using an inversion recovery GE sequence with different TIs and an overall acquisition time of approximately 100 minutes, T_1 is 1391 ± 37 ms, and variance is approximately 2.6% . Finally, the proposed method is employed to estimating T_1 of human brain, shown in Fig. 4. T1's across 5 normal subjects were: WM = 900 ± 3 ms, GM = 1337 ± 8 ms, CSF = 2180 ± 25 ms.

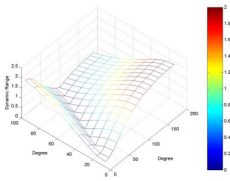

Fig1. The dynamic range of regression line as a function of the FA α_1 and α_2 at the TR/T_1=500 /1100 ms. The optimum FAs for minimizing error T_1 are 23° and 122°.

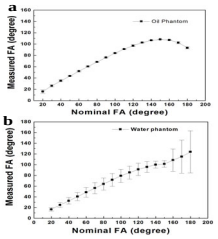

Fig 2. The linear relationship between the measured and the prescribed nominal FAs for oil (**a**) and milk (**b**) phantoms.

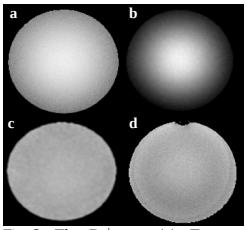

Fig 3. The B_1^+ map (**a**), T_1 map before (**b**) and after (**c**) correction of FA non-uniformity and calibration, and T_1 map measured by conventional inversion recovery (**d**).

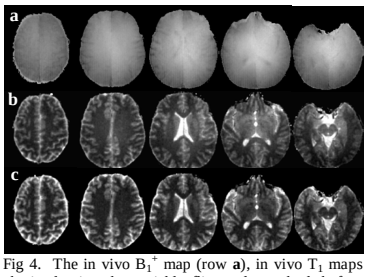

Fig 4. The in vivo B_1^+ map (row **a**), in vivo T_1 maps obtained using the variable flip angle method, before (row **b**) and after (row **c**) correction of FA non-uniformity and calibration.

CONCLUSION

(1) The assumption of a linear relationship between B_1^+ and flip angle holds up to approximately 260-280°. (2) RF calibration factors are 0.82 for oil phantom, 0.78 for milk phantom, and around 0.74 for human subjects at 3T. (3) With the correction and calibration of RF inhomogeneities, the variance of the T1 distribution decreased from 29% to 2.6% for homogeneous phantoms. (4) Acquisition times of the order of 6 minutes, including the measures of RF calibration and correction, yield *in vivo* T_1 images with high precision and accuracy. This approach makes rapid and accurate T_1 measurements at high field feasible for many *in vivo* applications.

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