Rapid High-Resolution T_1 Mapping by Variable Flip Angles: Accurate and Precise Measurements in the Presence of RF Field Inhomogeneity

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INTRODUCTION

Rapid 3D mapping of T_1 relaxation times is valuable in many clinical applications, including dynamic contrast-enhanced MRI of cancer, perfusion studies, and diagnosis of neurological disorders. Recently, the variable flip angle (VFA) spoiled gradient recalled echo (SPGR) approach was shown to offer a significant reduction in imaging time over conventional IR and SR techniques[1]. However, VFA is known to be sensitive to imperfect B_1 fields, which is ignored in most studies but can result in significant systematic errors in T_1 estimates. We develop theoretically the impact of B_1 variation and consider the influence of noise bias and choice of flip angles. Simulation, phantom, and in vivo human brain results validate improved accuracy of the proposed technique. Together, a set of methods is presented for accurate, precise, and rapid 3D T_1-mapping across a large T_1 range.

THEORY

The SPGR steady-state signal amplitude S_i acquired at flip angle α_i is a function of T_1, TR, and equilibrium magnetization M_o. The relaxation time T_1 can be estimated by acquiring signal at N different flip angles[2]. First-order error propagation shows that small errors in flip angle ($d\alpha$) due to B_1 variation result in the following error in T_1 [3]:

$$dT_1 = \frac{-T_1^2\exp(TR/T_1)}{TR\cdot N(\overline{X^2}-\overline{X}^2)}\sum_{i=1}^{N}\frac{d\alpha_i}{\tan\alpha_i}\left[Y_i\left(X_i-\overline{X}\right)+X_i\left(1+\tan^2\alpha_i\right)\left(Y_i-\overline{Y}-2\exp(-TR/T_1)\left(X_i-\overline{X}\right)\right)\right] \quad [1]$$

where $X_i = S_i/\tan\alpha_i$, $Y_i = S_i/\sin\alpha_i$, and $\overline{X},\overline{Y}$ are mean values. Eq.[1] states that the relative error in T_1 depends only on and is equal to twice the relative error in flip angle.

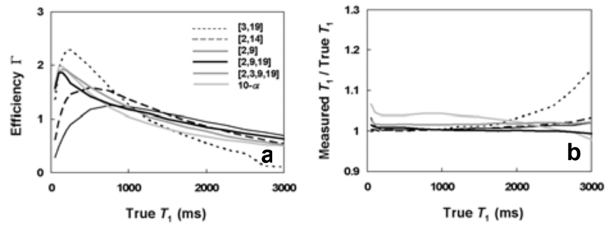

Fig.1. Simulated T_1 estimation for different flip angle sets: **(a)** efficiency and **(b)** accuracy. Multiple angles offer more uniform efficiency but increased sensitivity to noise-bias.

METHODS

T_1 estimation was simulated for T_1=50–3000 ms, beginning with signal generation for N angles α_i, TR=5 ms, M_o=1000, and zero-mean Gaussian complex noise (σ=M_o/SNR). Comparable imaging time was maintained by averaging multiple acquisitions (NEX) for sets with fewer angles. T_1 was estimated through weighted least-squares regression from 10,000 independent trials to obtain a mean ($\overline{T_1}$) and standard deviation (σ_{T1}). Noise bias was studied by varying SNR=150-1000. T_1 error due to angle (i.e. B_1) offsets was studied by varying true angles between 50-130% of nominal. Performance was assessed by the efficiency, or T_1-to-noise per unit imaging time: $\Gamma = (\overline{T_1}/\sigma_{T1})/\sqrt{TR\cdot NEX\cdot N}$.

Phantom experiments were performed on 8 solutions (T_1=50-3000 ms) at 1.5-T (Signa EXCITE TwinSpeed, GE) using a 3D fast SPGR sequence (TR/TE=4.4/1.1 ms). Signal averages matched simulations: 6 NEX for 2 angles, 4 NEX for 3 angles, and so on. In vivo brain scans were acquired in two volunteers at 3.0-T (Signa EXCITE Eclipse, GE) with the following parameters (TR/TE=6.1/1.5 ms, FOV=24 cm, SL=5 mm, matrix=256×256×28, 1 NEX). Transmit field B_1 maps were acquired in all MRI experiments using SE-EPI[4] (8 shots, TR=4000 ms, matrix=128×128, SL=4 mm, 60/120° and 120/240°). B_o offsets in SE-EPI were determined off-line from calibration scans against SE measurements on a phantom.

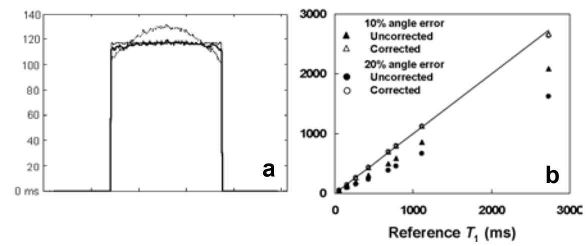

Fig.2. (a) Cross-section through T_1 map of single phantom before (dotted) and after (solid) B_1 correction – reference T_1 (thick). **(b)** Phantom T_1 measurements across the range 50-3000 ms.

RESULTS

Simulations confirmed significant T_1 error due to inaccurate flip angles (i.e. B_1 error), with the relative T_1 error equal to twice the relative angle error (Eq.[1]) when true angles were within 15% of nominal. The influence of flip angle selection is shown in Figure 1. In contrast to twin angles, which maximized efficiency Γ over a narrow T_1 range, multiple angles maintained consistently high Γ. The smallest set was achieved with 3 angles tuned to the minimum and maximum T_1 over the desired range (Fig.1a). Noise bias, apparent with larger angle sets, was minimal with 3 angles (Fig.1b).

Phantom results also validated our analytic expression for correcting B_1-induced error and confirmed our angle selection for optimal accuracy and precision. Accurate T_1 measurements in a single phantom and across a range of T_1 were obtained after B_1 correction (Fig.2). Three angles provided the highest and most uniform efficiency profile and the least sensitivity to noise bias (data not shown).

Human brain T_1-maps were more uniform within and between slices after B_1 correction (Fig.3). Total imaging for both T_1 and B_1 maps < 4 min.

CONCLUSIONS

A method is presented for accurate and rapid 3D VFA T_1-mapping across a wide range of T_1. Significant error can result from B_1 imperfections and noise bias. We successfully correct for these errors through a parameter-independent calibration curve (Eq.[1]) together with rapid B_1-mapping, and maintaining SNR above ~350. The optimal choice of flip angles is a set of three angles to ensure minimal sensitivity to noise bias and the best use of scan time for accurate and precise measurements across a large T_1 range.

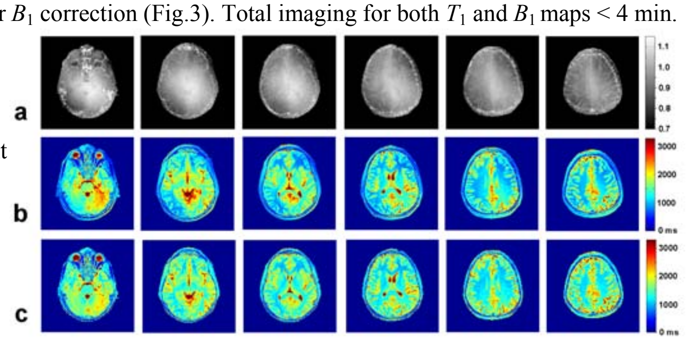

Fig.3. 3D T_1-mapping of human brain at 3.0-T. **(a)** B_1 field maps. **(b)** Uncorrected and **(c)** corrected T_1 maps acquired with 3 flip angles. Imaging time < 4 min.

REFERENCES

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