Simultaneous T_1, T_2, and B_1 Mapping Using Partially RF-Spoiled Gradient Echo

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Introduction

Quantitative parametric mapping in MRI is used to obtain distributions of MR parameters such as T_1 and T_2 relaxation times. MR parameters are estimated from MR images obtained with various acquisition parameters of a pulse sequence. For example, a T_1 map is estimated from images acquired by an inversion recovery sequence with various *TI*s (inversion times), and a T_2 or T_2^* map is estimated from images acquired with various *TE*s (echo times) by multiple spin-echo or gradient-echo (GrE) sequences. In the T_1 estimation at a magnetic field strength of 3T or higher, the effect of B_1 distribution also needs to be estimated.

In the estimation, the intensity function, which defines the relationship of image intensity to acquisition and MR parameters, is used to find MR parameter values that lead to a best fit of the intensity function to image intensity values as a function of acquisition parameters. The intensity function thus needs to be formulated analytically in a simple form. Therefore, the applicable pulse sequence is limited, and this makes it difficult to acquire images rapidly and to obtain multiple MR parameters simultaneously. We have proposed a method to formulate the intensity function numerically by using a computer simulation based on the Bloch equations [1]. The intensity function of rapid imaging of RF-spoiled GrE was formulated using this method and was successfully applied for T_1 and B_1 mapping.

It is also possible to simultaneously obtain multiple MR parameter maps such as T_1 and T_2 maps by applying a pulse sequence in which the intensity depends on these MR parameters. In this paper, we formulate the intensity function for simultaneous estimation of T_1, T_2, and B_1 maps by using partially RF-spoiled GrE in which the intensity depends on T_2 in addition to T_1 by changing the RF phase in RF-spoiled GrE. We confirmed that these three maps were well estimated from images obtained in a phantom experiment.

Method

A schematic diagram of the pulse-sequence simulator used to formulate the intensity function is shown in Fig. 1. The inputs to the simulator are the subject model (as distributions of density of spins with relaxation times T_1 and T_2) and the pulse sequence. The Bloch equations are solved for each spin in the subject model at an arbitrary time, according to the given pulse sequence. In solving the equations, the transition-matrix method and an analytical solution are used, and the effects of T_1 and T_2 are factored into both calculations [2]. The echoes are then obtained by calculating the vector sum of the spins.

This simulator was used to formulate the intensity function for partially RF-spoiled GrE. This sequence is a fast and efficient pulse-sequence, and its intensity function is formulated analytically; however, the function is not simple enough for estimation of MR parameters. The subject model is shown in Fig. 2, where the spin density was uniform while T_1 and T_2 were distributed from 50 – 3000 ms in the x direction and 30 – 1500 ms in the y direction, respectively. The image contrast of partially RF-spoiled GrE depends on the acquisition parameters of repetition time (*TR*), flip angle (*FA*), and phase cycling of RF (θ). Three-hundred images with different contrast were acquired by the simulator with different *TR*, *FA*, and θ values: 10, 15, 20, 25, and 30 ms for *TR*, 1, 3, 4, 10, 15, 20, 30, 40, 50, and 60 degrees for *FA*, and 0, 1, 3, 5, 8, and 12 degrees for θ. The intensity function $f(T_1, T_2, TR, FA, \theta)$ was formulated numerically by cubic polynomial interpolation of the intensity of these images.

MR parameter values of T_1, T_2, and B_1 were estimated using the intensity function in a phantom experiment on a 1.5T MRI system. The phantom, as shown in Fig. 3, was composed of solutions of NiCl in water with four different concentrations: 1, 1.5, 2.5, and 5 mM with respective relaxation times (T_1, T_2) of (1036, 813), (745, 596), (466, 384), and (297, 254) ms. Sixteen optimal parameter sets were selected from twenty combinations of *FA* and θ: 10, 20, 30, 40, and 50 degrees for *FA* and 0, 2, 6, and 12 degrees for θ using the law of error propagation with target parameters T_1 and T_2 of 800 ms (Fig. 4). *TR* was fixed at 20 ms. Other acquisition parameters were as follows—matrix size: 128×128, field of view: 250 mm, *TE*: 5 ms, and bandwidth: 20 kHz. Least squares fits were then found with the following equation to obtain values of T_1, T_2, B_1, and a:

$$\chi^2 = \sum_{\theta}\sum_{TR}\sum_{FA}\left\{\frac{I(TR,FA,\theta) - a\,f(T_1,T_2,B_1 FA,TR,\theta)}{I(TR,FA,\theta)}\right\}^2 = \text{min},$$

$$0.05 < T_1 < 3,\ 0.03 < T_2 < 1.5,\ 0.5 < B_1 < 1.2,\ 0 < a,$$

where $I(TR,FA,\theta)$ is the intensity of the phantom images, and a is a coefficient representing spin density and receiver coil sensitivity.

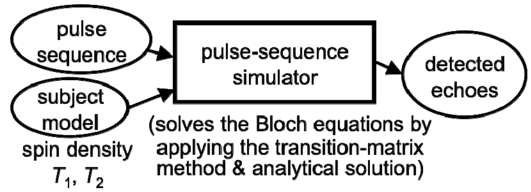

Fig. 1: Pulse-sequence simulator.

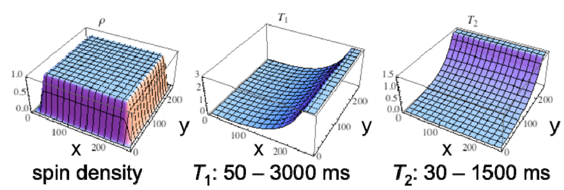

Fig. 2: Subject model for pulse-sequence simulation.

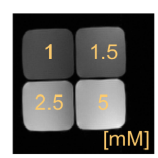

Fig. 3: NiCl phantom.

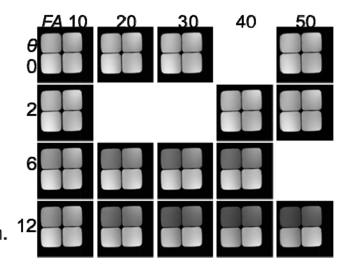

Fig. 4: images selected for estimation.

Results and Discussion

The results of T_1 and T_2 mapping obtained by the estimation are shown in Fig. 5 and Table 1, and the estimated B_1 and a are shown in Fig. 6. In Fig. 6, a B_1 map obtained by using the double-angle method (DAM), and coil sensitivity are also shown for comparison. In Fig. 5 and Table 1, it is confirmed that T_1 and T_2 values are well estimated and that the errors of the values are less than or equal to 9% and 14%, respectively. The B_1 map is also well estimated compared with DAM, as shown in Fig. 6.

The parameter of a is possibly proportional to the coil sensitivity because the subject is a phantom with an almost uniform density. In a comparison between a and coil sensitivity in Fig. 6, it is clear that a is slightly smaller than coil sensitivity at the periphery of the field of view, but they agree in the tendency for the amplitude to decrease toward the center of the field of view.

We also estimated T_1, T_2, and B_1 values with a *TR* of 10 ms instead of 20 ms. In this case, the value of the objective function of the error propagation was worse, and only the long T_2 value (813 ms) was not correctly estimated (estimated T_2 was 611 ms). The other values were well estimated, as was the case with a *TR* of 20 ms. The reason for this is that the T_2 decay is small in the case of a short *TR* (10 ms), and the intensity function does not depend on T_2 enough to estimate a long T_2. It is necessary to evaluate the estimation using the sequence parameter of a longer *TE* than 5 ms to enable *TR* to decrease for faster acquisition.

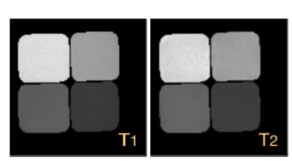

Fig. 5: T_1 and T_2 maps.

Table 1: T_1 and T_2 values.

NiCl [mM]	T_1 [ms]	T_2 [ms]
1	1129±29 (+8.9%)	758±35 (-6.7%)
1.5	808±22 (+8.4%)	557±23 (-6.5%)
2.5	479±13 (+2.8%)	353±13 (-7.9%)
5	299±12 (+0.6%)	219±8 (-14%)

mean±SD (error%)

Conclusion

We have confirmed that our proposed method can be applied to estimate T_1, T_2, and B_1 maps simultaneously using a fast pulse sequence of partially RF-spoiled GrE. The estimation is based on the intensity function formulated numerically by computer simulation.

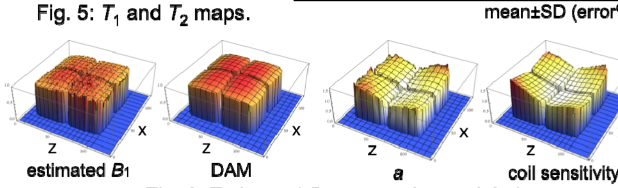

Fig. 6: Estimated B_1 map and a, and their comparison with DAM and coil sensitivity.

References

[1] Taniguchi, Y et al., ISMRM, 3113, 2010.

[2] Taniguchi, Y et al., Systems and Computers in Japan, 26: 54, 1995.