Magnetic Resonance Parameter Mapping Using Computer Simulation

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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 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 sequences. In the estimation, the intensity function, which defines the relationship of image intensity to acquisition parameters and MR parameters, is used to find MR parameter values that make the intensity function give a best fit 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.

In this paper, we propose a method to formulate the intensity function numerically by using a computer simulation based on the Bloch equations. Intensity functions of arbitrary pulse sequences for rapid imaging are formulated using this method so that the rapid imaging is applied for MR parameter mapping. It is also possible to obtain multiple parameters simultaneously by applying a pulse sequence in which the intensity depends on multiple MR parameters. The intensity function for RSSG (rf-spoiled steady-state acquisition with rewound gradient echo) was formulated numerically, and we confirmed that a T_1 map was 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 [1]. The echoes are then obtained by calculating the vector sum of the spins.

This simulator was used to formulate the intensity function for RSSG. 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 are distributed from 50 – 3000 ms in the x direction and 30 – 1500 ms in y, respectively. The image contrast of RSSG depends on the acquisition parameters of repetition time (*TR*) and flip angle (*FA*). Forty-five images with different contrast were acquired by the simulator with different *TR* and *FA*: 10, 15, 20, 25, and 30 ms for *TR* and 1, 3, 4, 10, 15, 30, 40, 50, and 60 degrees for *FA*. The intensity function $f(T_1, T_2, TR, FA)$ was formulated numerically by cubic polynomial interpolation of the intensity of these images.

MR parameter values of T_1 and T_2 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 five different concentrations: 1, 5, 15, 20, and 25 mM with respective relaxation times (T_1, T_2) of (895, 764), (292, 275), (104, 99), (82, 79), and (72, 62) ms. Thirty-five RSSG images of the phantom were acquired with *TR* of 10, 15, 20, 25, and 30 ms and *FA* of 15, 20, 25, 30, 35, 40, and 45 degrees. Other acquisition parameters were as follows—matrix size: 128×128, field of view: 180 mm, *TE*: 5 ms, and bandwidth: 20 kHz. The matrix size was reduced to 64x64 by adding values of four pixels before the parameter estimation. Least squares fits were then found with the following equation to obtain values of T_1, T_2, *a*, and *b*:

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

where *I*(*TR*, *FA*) is the intensity of the phantom images, a is a coefficient representing spin density and receiver coil sensitivity, and b is RF field strength.

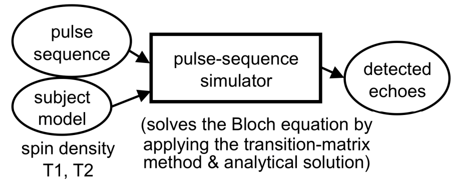

Fig. 1: Pulse-sequence simulator.

Results and Discussion

A comparison of intensity functions obtained by simulation and a phantom experiment is shown in Fig. 4. The figure shows that both functions agree well, but they differ slightly because *FA* in the case of the experiment is not precise due to the inhomogeneity of the RF field.

The results of T_1 and T_2 mapping obtained by the estimation using 35 and 9 images are shown in Fig. 5a and 5b, respectively. Each figure shows a profile on the line depicted in Fig. 3. In Fig. 5a, it is confirmed that T_1 values are well estimated and that the errors of the values are less than or equal to ±20%. On the other hand, T_2 values are not estimated correctly because the image contrast of RSSG does not depend on T_2 values. To estimate T_2 values, it is necessary to induce T_2 contrast in RSSG images by changing the phase modulation of RF pulses.

In Fig. 5b, it is confirmed that T_1 is also well estimated except for the 1-mM phantom using only nine images. This is because the estimation accuracy depends on the signal-to-noise ratio (S/N) of the images, and the S/N of the 1-mM phantom image is lower than that of the other images. The S/N of each phantom was 194, 180, 166, 114, and 52 with *TR* of 20 ms and *FA* of 30 degrees.

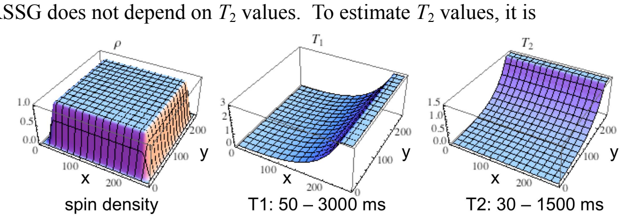

Fig. 2: Subject model.

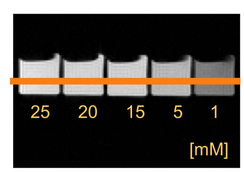

Fig. 3: NiCl phantom.

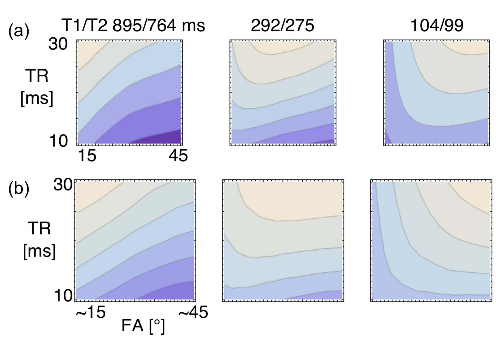

Fig. 4: Intensity functions obtained by (a) simulation of present method and (b) phantom experiment.

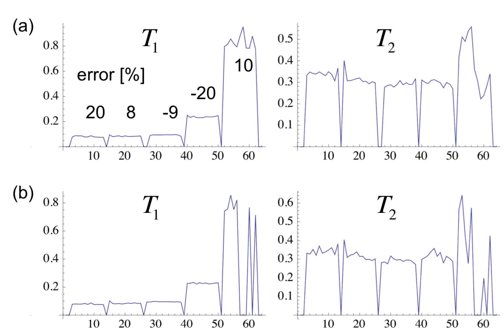

Fig. 5: Profiles of phantom MR parameters estimated using (a) all of 35 images and (b) 9 images.

Conclusions

We have confirmed that our proposed method can be applied to estimate MR parameter maps using intensity functions formulated numerically by computer simulation and that it is possible to apply the fast pulse sequences to the estimation. To estimate multiple MR parameters including T_1 and T_2 using RSSG, it is necessary to change the phase modulation of RF pulses.

References

[1] Taniguchi, Y et al., IEICE Trans. Inf. & Syst., J77DII: 566, 1994.