A Simulation of MR Imaging Sequences Using the Numerical Solutions of Bloch Equations

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Abstract

We design a computer simulation program to solve the Bloch Equations. By applying different RF pulse sequences, we can simulate MR images and their imaging contrasts for material with different T1 and T2. The imaging contrast fits well with the calculated formula value. For a RF pulse sequence does not have a signal close form intensity, we can use this program to simulate the images and their T1, T2 contrasts.

Introduction

Many RF pulse sequences have their close form formulae of signal intensity. But not every RF pulse sequence has such a formula. Using this simulation program we can find the signal amplitude and imaging contrast properly. Here we apply it in typical RF pulse sequences : CPMG experiment, Stimulated Echo [1], Conventional Spin Echo Imaging, Conventional Gradient Echo Imaging, Gradient-Recalled Acquisition in the Steady State Imaging (GRASS) [2] and Stimulated Echo Acquisition Mode (STEAM) Imaging [1].

Method

The Bloch Equations in the rotating frame are :

$$\frac{dM_x}{dt} = \gamma(M_y\Delta B_0 - M_z B_{1y}) - \frac{M_x}{T_2}$$

$$\frac{dM_y}{dt} = \gamma(-M_x\Delta B_0 + M_z B_{1x}) - \frac{M_y}{T_2}$$

$$\frac{dM_z}{dt} = \gamma(M_x B_{1y} - M_y B_{1x}) - \frac{M_z - M_0}{T_1}$$

where Mx, My, Mz is the magnetization of x, y, and z axes, respectively. γ is 4257 Hz/gauss, ΔB_0 is the field difference from the mainly magnetic field B_0, and B_{1x}, B_{1y} is the RF pulse on x and y axis, respectively. Here we use RK 4th method to solve these differential equations.

In this simulation we assume that we are in the ideal situation, i.e. : rectangular gradient wave forms, no field inhomogeneity and perfect refocusing RF pulse.

The parameters of each RF pulse sequence are given in Table 1. and Table 2. The variable h is the time resolution in the RK 4th method. α ° RF amplitude in these pulse sequence can be calculated as $\alpha° = 0.0587*5*10^{-6}* \alpha /(h*90)$ gauss.

In CPMG experiment, we use 19 spins in simulation. The four echo simulated result is given in Fig. 1.

In Stimulated Echo (STE), the simulated spin number is 299. The RF pulse sequence is $90°_x$-5ms-$90°_x$-15ms-$90°_x$. Fig. 2. shows the simulation echo trains.

In imaging simulation, there are two phantoms with the same proton density for imaging, the left one, phantom A and the right one, phantom B. The image sizes are all 64x64.

The simulated image for Conventional Spin Echo is given in Fig. 3. The signal intensity formula is given as,

$$S \propto [1 - 2\exp(-\frac{TR - \frac{TE}{2}}{T_1}) + \exp(-\frac{TR}{T_1})]\exp(-\frac{TE}{T_2}) \qquad (1)$$

Figure 4. shows the simulated image of Conventional Gradient Echo. The signal intensity is,

$$S \propto (1 - \exp(-\frac{TR}{T_1})) * \exp(-\frac{TE}{T_2^*}) \qquad (2)$$

Here we set $T^*_2=T_2$.

In the GRASS imaging, the flip angle α is 45°. After the read gradient, we place a rewinder gradient on the phase-encoding axis to undo the phase shift induced by the phase-encoding gradient. The result is in Fig. 5. The signal intensity can be shown as,

$$S \propto \frac{\sin(\alpha)}{1 + \frac{T_1}{T_2} - \cos(\alpha) * (\frac{T_1}{T_2} - 1)} \qquad (3)$$

In STEAM Imaging, the RF pulse sequence is $90°_x$-5.5ms-$90°_x$-46.5ms-$90°_x$-6.5ms-Echo. The phase-encoding gradient is turned on after the third $90°_x$ pulse. The simulated image is shown in Fig. 6.

	h (ms)	T1 (ms)	T2 (ms)	Gx (gauss/cm)
CPMG	0.005	200	80	0.02
STE	0.0005	200	80	0.015

Table 1.

Results and Discussion

Refocusing Time In complicated MR sequence, echo time is not trivial to predict. For burst imaging and stimulated-echo based sequences, we show that simulation results can give exact echo time as one expects (Fig. 2).

Image Contrast The imaging contrast results are given in Table 3. These simulated contrasts fit well with the calculated values. STEAM imaging sequence, as one expects, shows

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	h (ms)	TR (ms)	TE (ms)	Phantom A	Phantom B	Gx (gauss/cm)	Gy (gauss/cm)	resolution of x (mm)	resolution of y (mm)
SE	0.005	400	60.5	T1=200 ms T2=100 ms	T1=100 ms T2=50 ms	0.5	0.0015	0.91	0.96
GE	0.005	400	53.7	T1=200 ms T2=100 ms	T1=100 ms T2=50 ms	0.5	0.0015	0.91	0.96
GRASS	0.0005	21	10.49	T1=100 ms T2=50 ms	T1=150 ms T2=50 ms	0.1	0.00312	2.29	2.29
STEAM	0.0005	1352	58.5	T1=200 ms T2=50 ms	T1=80 ms T2=50 ms	0.1	0.012	2.35	2.45

Table 2.

T1-weighted contrast behavior.

Limitation The solutions will converge under certain imaging parameter ranges. These parameters affecting phase angle should be choose carefully. Dynamic RK method is developed to increase efficiency of simulation.

For further study, we are simulating more new RF pulse sequences such as Burst imaging. Also, trade-off between simulation spin number and computing time will be carefully optimized.

S_A : S_B	Theoretical Value	Simulated Value	Error Ratio
Spin Echo	1.55:1	1.53:1	-1.29 %
Gradient Echo	1.51:1	1.50:1	-0.6 %
GRASS	1.13:1	1.16:1	2.65 %
STEAM		1.25:1	

Table 3.

Reference

[1] J. Frahm, et. al, "Stimulated Echo Imaging.", J. Magn. Reson. 64, 81-93 (1985).

[2] Felix W. Wehrli, "Fast-Scan Magnetic Resonance Principles and Applications", Raven Press, New York, 1991.

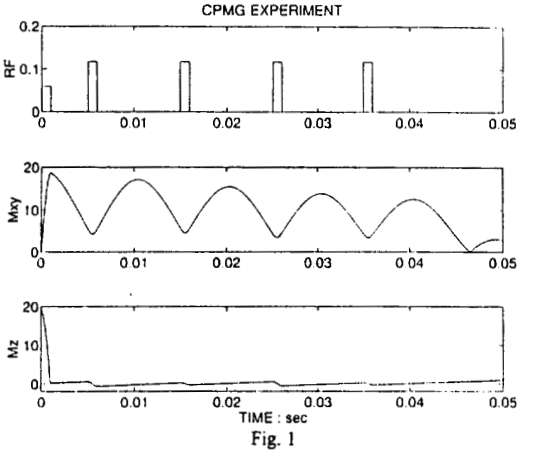

Fig. 1

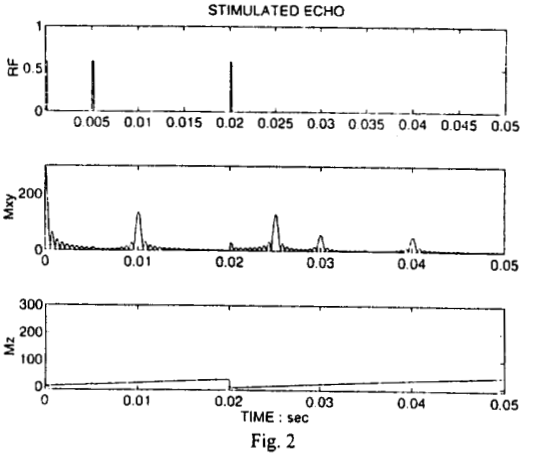

Fig. 2

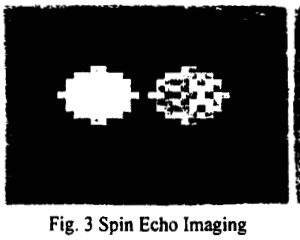

Fig. 3 Spin Echo Imaging

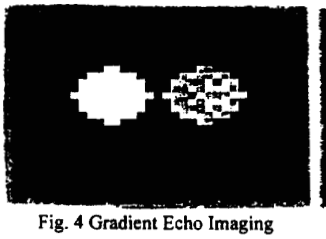

Fig. 4 Gradient Echo Imaging

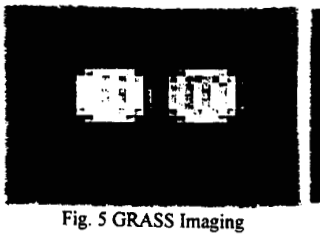

Fig. 5 GRASS Imaging

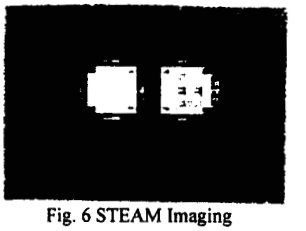

Fig. 6 STEAM Imaging