Computer Simulation for Evaluating MR Image Artifacts Caused by Magnetic Field Fluctuations Induced by Gradient Pulses

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Introduction

Temporal fluctuations in a magnetic field produce artifacts and distortion in MR images. The main sources of such fluctuations are eddy currents, which are induced by gradient switching. Fluctuations induced by gradient switching cause significant effects in MR images, especially in DWEPI (diffusion weighted echo-planar imaging), that uses MPG (motion probing gradient) pulses with a huge amplitude. However, we lack good tools for evaluation of the effects caused by temporal fluctuations from gradient switching.

We developed a pulse-sequence simulator for evaluation of arbitrary temporal fluctuations in the magnetic field caused by external vibrations such as those produced by cryocoolers [1]. However, evaluating the fluctuations caused by gradient switching by using the simulator is not so easy because the temporal fluctuation data under the gradient switching should be calculated by some means such as computer simulations of electromagnetic field.

In this paper, we describe an extension of the pulse-sequence simulator for easy evaluation of MR image quality in the presence of temporal fluctuations of the magnetic field caused by gradient switching. The fluctuation data are given as feature parameters, which are inputs to the simulator. The feature parameters of the fluctuations are spatial distributions of amplitude, decay time constant, frequency, and phase. We confirmed that geometrical distortions in images obtained by DWEPI simulations correspond well with those from the experiments when eddy currents are intentionally increased.

Method

A schematic diagram of the pulse-sequence simulator 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), the pulse sequence, and the feature parameters for temporal fluctuations of a static magnetic field induced by gradient switching. The temporal fluctuations, ΔH, are shown in Fig. 2 and defined in the following equations using the feature parameters:

$$\Delta H(x,y,z,t) = \sum_{j=1}^{M} \Delta H_j(x,y,z,t), \quad \Delta H_j(x,y,z,t) = \sum_{i=1}^{N} g_j k_i(x,y,z) e^{-(t-t_j)/T_i} \cos(\theta_i + 2\pi f_i (t - t_j)),$$

where g_j is gradient amplitude, $k_i(x, y, z)$ is the ratio of amplitude at position (x, y, z), T_i is decay time constant, f_i is frequency, θ_i is phase, N is the number of feature parameters, and M is the number of gradient-switching times.

In the simulator, the Bloch equations are solved for each spin in the subject model at an arbitrary time, according to the given pulse sequence and fluctuations. 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.

The simulator was used to calculate DWEPI taken in the presence of increased eddy currents. The parameters of the pulse sequence were as follows—slice: axial AP, matrix size: 128×128, field of view (fov): 250 mm, TR: 1000 ms, TE: 65 ms, MPG: AP or RL, b-factor: 500, echo train length: 72, inter echo time: 1 ms. The eddy currents were added in the simulation with a linear spatial distribution in the same direction as that of gradient pulses, amplitude ratio of 1%, and a decay time constant of 350 ms. The subject model was a circle 165 mm in diameter with slits in both horizontal and vertical directions, and placed in the center of the fov. The spin distribution in the model was uniform, and T_1 and T_2 for the spins were 800 and 100 ms. The number of spins needed for sufficient calculation accuracy is sixteen per pixel, that is, four per pixel in both the readout and phase-encoding directions [2].

Images were also obtained in a phantom experiment on a 1.5-T horizontal system using a pulse sequence with the same parameters as those of the simulation for comparison with the simulation results. Eddy currents were increased in the experiment by manually changing the same parameters (amplitude ratio of 1% and decay time constant of 350 ms) as those of the simulation for the eddy current compensation system. The diameter of the phantom (165 mm) was also the same as that of the simulation.

Results and Discussion

A comparison of simulated and experimental images obtained using DWEPI is shown in Fig. 3. In both cases where eddy currents are increased, geometrical distortions appear when MPG is applied. In the case of MPG direction of RL, which is the frequency-encoding direction, the image is skewed, and in the case of MPG direction of AP, which is the phase-encoding direction, the fov becomes small in the AP direction. The geometrical distortions in the simulated images are the same sizes as those of the experimental images. Calculations were done on five Linux PCs each with two CPUs (2-GHz Xeon, ten CPUs in total) by parallel computing using MPI (message passing interface), and this took about 40 s per image for the simulation.

The pulse-sequence simulator quantitatively evaluates the effects on images caused by eddy currents induced by gradient pulses. Therefore, the extended simulator will be a more powerful tool for the quantitative evaluation of image quality, of algorithms to correct for the fluctuations, and of the performance of magnets and gradient coils.

Conclusion

We have described an extension of our MRI pulse-sequence simulator to handle temporal fluctuations induced by magnetic field gradient switching. We compared simulated and experimental images to evaluate the simulation, and those geometrical distortions were same. This shows the power of the simulator in the evaluation of image quality. The extended simulator will also be useful in the quantitative evaluation of algorithms to correct for fluctuations and performance of magnets and gradient coils.

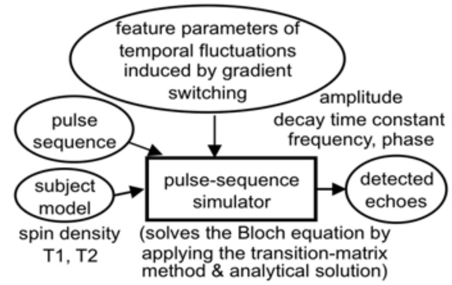

Fig. 1: Pulse-sequence simulator including feature parameters of fluctuations induced by gradient switching.

References

[1] Taniguchi, Y et al., ISMRM, 2244, 2005.
[2] Taniguchi, Y et al., IEICE Trans. Inf. & Syst., J77DII: 566, 1994.

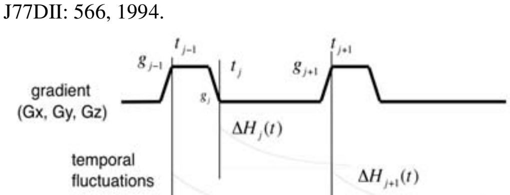

Fig. 2: Definition of temporal fluctuations induced by gradient switching.

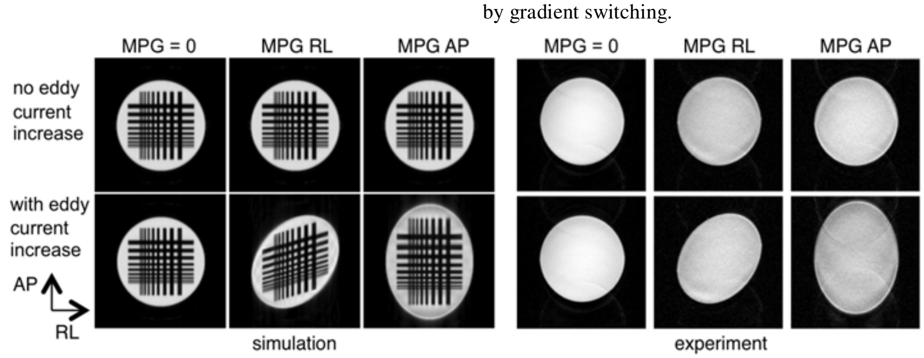

Fig. 3: Simulated and experimental images obtained using DWEPI.