Computer Simulation for Evaluating MR Image Quality in the Presence of Temporal Magnetic Field Fluctuations

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Introduction

Spatial and temporal fluctuations in magnetic field produce artefacts and distortion in MR images. Spatial fluctuation has two components: inhomogeneity of the static magnetic field and non-linearity of the magnetic field gradients. The artifacts and distortions produced by such fluctuations have been evaluated for various pulse sequences, and various methods for suppressing these effects have been proposed. Spatial fluctuations are conventionally taken as defining the performance of the magnets of MRI apparatus.

However, fluctuations in the magnetic field over time have not yet been comprehensively examined from the points of view of image quality and the performance of magnets. The main sources of such fluctuations are vibration of the magnet, which is due to gradient switching or external vibration, and eddy currents, which are induced by gradient switching. While such fluctuations have significant effects, we lack good tools for their evaluation. So far, the evaluation and correction of fluctuations over time has been limited to particular pulse sequences, such as those used in echo planar imaging, and these fluctuations have not been considered in the evaluation of magnet performance.

In this paper, we extend our pulse-sequence simulator to cover the evaluation of MR image quality in the presence of temporal fluctuations of the magnetic field. The simulator is used to calculate GE (gradient-echo) images, and the result confirms that temporal fluctuations can produce significant artefacts.

Method

Figure 1 is a schematic diagram of the pulse-sequence simulator. The inputs to the simulator are the subject model (as distributions of density of spins with relaxation times T1 and T2), the pulse sequence, and temporal and spatial fluctuations of the magnetic field. The temporal and spatial fluctuations are described as simple harmonic oscillations or as arbitrary fluctuations. In the case of simple harmonic oscillation, the description takes the form of the amplitude, frequency, and phase at the location of each spin. Arbitrary fluctuations are defined as differences in magnetic field strength from the static field strength at the locations of the respective spins, sampled at a constant time step. 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 T1 and T2 are factored into both calculations [1, 2]. The echoes are then obtained by calculating the vector sum of the spins.

The simulator was used to calculate GE images taken in the presence of temporal fluctuations. The parameters of the pulse sequence were as follows—matrix size: 128x128, field of view: 260 mm, TR: 500 ms, TE: 10 ms. The temporal fluctuations were spatially homogeneous simple harmonic oscillations, with a peak-to-peak amplitude of 2 μT. This was intended to represent vibrations such as those produced by cryocoolers. The phase of a fluctuation of this kind affects the intensity of the artefacts, so the phase of the oscillations were set to 0 and $\pi/2$ radian. The frequency of oscillation was set to 1 Hz, so that the fluctuation is phase-inverted on every TR and thus produces relatively strong image degradation.

The subject model was a circle 200 mm in diameter with slits in both horizontal and vertical directions, and placed in the center of the field of view. The spin distribution in the model was uniform, and T1 and T2, relaxation times for the respective spins, were 800 and 100 ms. The number of spins needed for sufficient accuracy in calculation is sixteen per pixel, that is, four per pixel in both the readout and phase-encoding directions [1].

Results and Discussion

Calculations were done on a Linux PC with a 1.8-GHz AMD Opteron and took about 15 min per image. Figure 2 is a comparison of simulated GE images with and without fluctuating magnetic fields. In both cases where fluctuations are present, N/2 ghosts appear (Fig. 2b and 2c). The artefacts are significantly stronger in the image where the phase of the fluctuations is $\pi/2$ (Fig. 2c) than in that where the phase is 0 (Fig. 2b). This is because of the greater phase error of the echoes in the case of Fig. 2c.

The pulse-sequence simulator can also calculate echoes obtained in the presence of arbitrary fluctuations in both space and time. The fluctuations can be experimentally measured or obtained through computer simulation of the magnet. Therefore, the extended simulator will be a more powerful tool for the quantitative evaluation of image quality, of algorithms to correct for fluctuations in time as well as space, and of the performance of magnets.

Conclusion

We have described an extension of our MRI pulse-sequence simulator to handle temporal fluctuations of magnetic field strength. We use the simulator to demonstrate a case where fluctuations caused by vibrations external to the magnet cause N/2 ghosts in GE images. 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 over time and of the performance of magnets.

References

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

[2] Taniguchi, Y et al., ISMRM, 862, 2002.

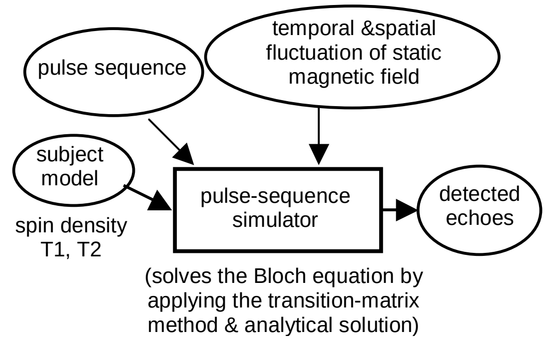

Fig. 1: Pulse-sequence simulator including consideration of temporal fluctuations of the magnetic field.

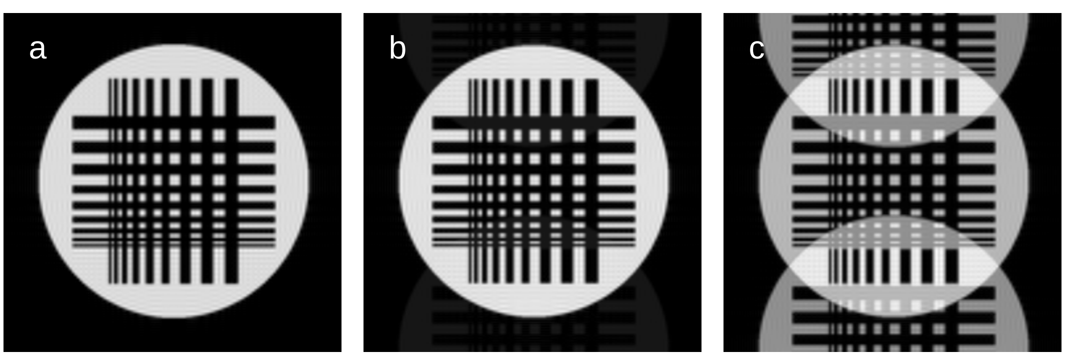

Fig. 2: Simulated GE images (a) without and (b, c) with temporal fluctuations of the magnetic field. The fluctuations are simple harmonic oscillations with phases of (b) 0 and (c) $\pi/2$.