Detection of Weak Magnetic Fields Induced by Electrical Currents Using MRI: Theoretical Sensitivity Limits and Related Experiments

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Abstract

Detection of weak magnetic fields induced by electrical currents is necessary for the mapping of neuronal electrical activities in the brain. In this study, we analyzed the theoretical sensitivity limits of magnetic field strength change from the gradient echo (GE) phase image by computing the theoretical value of signal and noise. We also performed related experiments. In the case of the columnar phantom injected with a pulsed electrical current, the theoretical limit was 10^{-9}T and the experimental limit was 10^{-8}T. The variance in the theoretical limits of the detectable change in magnetic field strength was computed by modifying the parameters.

Introduction

The imaging of magnetic fields produced by local current flows is important for the mapping the patterns of neuronal activity in the brain. It is difficult, however, to detect the weak transient magnetic fields caused by neural electrical currents. We computed the theoretical sensitivity limits of the magnetic fields from gradient echo (GE) phase images, based on the theory of the signal-to-noise ratio in magnetic resonance imaging.

Theory

The GE signal strength S_{GE} can be calculated using the following equation [1],

$$S_{GE} = S_{FID} \times \frac{\{1-\exp(-T_R/T_1)\}\exp(-T_E/T_2^*)}{1-\cos\theta\exp(-T_R/T_1)}\sin\theta = N_S V_S \omega_0 (B_1/i)\gamma^2\hbar^2 B_0 I(I+1)/3k_B T_S \times \frac{\{1-\exp(-T_R/T_1)\}\exp(-T_E/T_2^*)}{1-\cos\theta\exp(-T_R/T_1)}\sin\theta \quad (1)$$

where S_{FID} is the FID signal strength, N_S is the number of proton spins per unit volume in water (5.1×10^{18}m^{-3}), V_S is the volume of the sample in an image, ω_0 is the resonance frequency, B_1/i is the magnetic generated by the unit current flowing in the coil, γ is the gyromagnetic ratio for protons (2.67×10^{8}rad/T·s), $\hbar$ is the Plank constant (1.05×10^{-34}J·s), B_0 is the static magnetic field, I is the spin quantum number for protons (1/2), k_B is the Boltzmann constant (1.38×10^{23}J/K), T_S is the sample temperature, and θ is the flip angle. The Johnson noise produced by the coil and the columnar sample N is

$$N = \{4k_B\Delta f(R_C T_C + R_S T_S)\}^{1/2} = [4k_B\Delta f\{(l/p)(\mu_r\mu_0\omega_0\rho/2)^{1/2}T_C + \frac{1}{8}\sigma_S\omega_0^{\ 2}(B_1/i)^2 r_S^{\ 4}h\}]^{1/2} \quad (2)$$

where Δf is the spectral width, R_C, R_S is the coil and sample resistance, T_C is the coil temperature, l is the coil length, p its circumference, $\mu_r\mu_0$ its permeability, ρ its resistivity, σ_S is the sample conductivity, r_S its radius and h its height. Since in the GE phase image construction a two-dimensional Fourier Transformation is effected, the noise in the magnetic fields image σ_B becomes

$$\sigma_B = \frac{1}{SNR(FI)\gamma T_E} = \frac{N(FI)}{S_{GE}(FI)\gamma T_E} = \frac{nN}{(4/\pi)n^2 n_S^{\ 2} S_{GE}\gamma T_E} = \frac{N}{(4/\pi)n n_S^{\ 2} S_{GE}\gamma T_E} \quad (3)$$

where n is the number of pixels, and n_S is the data point which corresponds to the diameter of the sample. The noise in the magnetic field image σ_B can be assumed to constitute the theoretical limits of the detectable magnetic field change, since the magnetic field change produced by the weak current can be detected when it is larger than σ_B.

Experiments

To compute the actual value of the detectable magnetic field change, we obtained a magnetic field image using a 4.7 T MRI system under the following conditions. Rectangular current pulses (10mA, 5mA, 2mA,…,10μA) were passed through the columnar phantom filled with a mixture of 1 % agarose gel and 0.9 % NaCl solution ($r_S = 7\times10^{-3}$m, $h = 6.2\times10^{-2}$m, $V_S = 7.7\times10^{-8}$m^3, $T_S = 295$K, $\sigma_S = 2.0$S/m) within the circular surface coil ($l = 8.8\times10^{-2}$m, $p = 5.0\times10^{-3}$m, $\mu_r\mu_0 = 1.26\times10^{-6}$H·m^{-1}, $\rho = 1.72\times10^{-8}\Omega$·m, $B_1/i = 4.49\times10^{-5}$T/A) to obtain images. The image parameters were $B_0 = 4.7$T, $T_R/T_E/\theta = 900$ms/20ms/90˚, $FOV = 32\times32$mm^2, $n = 64$, $\Delta f = 28449.5$Hz, and the thickness of slice = 0.5mm. In this measurement, $\omega_0 = 1.26\times10^{9}$rad/s, $n_S = 28$, $T_1 = 2.50$s, $T_2^* = 71.2$ms.

Using a theoretical equation, we performed the noise variance simulations of the magnetic field change, modifying the parameters: T_R/T_1, TE/T_2^*, number of pixels and spectral width.

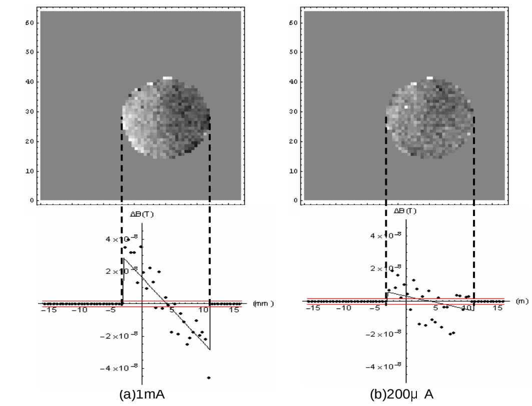

Fig. 1. Magnetic field image and theoretical value (a) 1mA, (b) 200μA

Results and Discussion

The magnetic field change images, after the application of 1mA and 200μA ,as well as the theoretical graphs, are shown in Fig.1. Under these conditions, the theoretical sensitivity limit σ_B is 1.68×10^{-9}T. At 1mA, the magnetic field changed along the theoretical graph, but at 200μA, it was disturbed by the noises.

Fig.2 shows results of the noise variance simulations of the magnetic field change images obtained by modifying the parameters: (a) T_R/T_1, (b) TE/T_2^*, (c) number of pixels and (d) spectral width. Fig.2 (b) shows that there is an optimal value for TE/T_2^*.

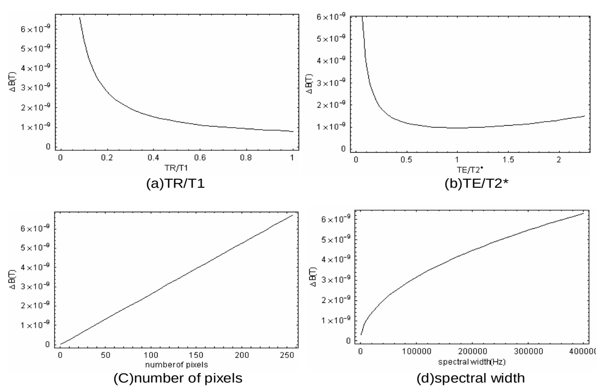

Fig. 2. Theoretical sensitivity limits variance of detectable magnetic field by modifying the parameters (a)T_R/T_1, (b)T_E/T_2^*, (c)number of pixels, (d)spectral width

Reference

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