Magnetic resonance imaging of a magnetic field generated by electric current based on a shift in the resonant frequency

M. Sekino[1], T. Matsumoto[1], K. Yamaguchi[1], N. Iriguchi[2], S. Ueno[1]

[1]Department of Biomedical Engineering, Graduate School of Medicine, University of Tokyo, Tokyo, Japan, [2]Center for Multimedia and Information Technologies, University of Kumamoto, Kumamoto, Japan

Introduction

Because MRI is an effective method for direct detection of electric currents inside tissues, several principles to obtain electric-current-dependent contrast have been proposed, such as observation of a phase shift in the Larmor precession [1], modulation of echoes by the radiofrequency (RF) pulse [2], and measurement of the apparent diffusion coefficient [3]. In this study, we propose a new method for imaging a magnetic field generated by electric current based on a shift in the resonant frequency.

Theory

Figure (a) shows the pulse sequence used in this study. The first electric current pulse is applied simultaneously with the excitation RF pulse to cause a shift in the resonant frequency. The second electric current pulse is applied to rewind the transverse magnetization. The excitation RF pulse has the Gaussian waveform with a duration of 10 ms and a peak amplitude of 1.4 μT. To investigate the effects of the applied electric current on signals, we analyze the motion of magnetization during applications of the first electric current pulse and the excitation RF pulse using the rotating-frame Bloch equation:

$$\frac{dM'_x}{dt} = -\gamma M'_z B_1 \sin \gamma b_z t \qquad \frac{dM'_y}{dt} = \gamma M'_z B_1 \cos \gamma b_z t \qquad \frac{dM'_z}{dt} = \gamma M'_x B_1 \sin \gamma b_z t - \gamma M'_y B_1 \cos \gamma b_z t \tag{1}$$

where b_z is the component of the generated magnetic field in the direction parallel to the static magnetic field (z direction), and B_1 is the amplitude of the RF pulse. Figure (b) shows the time course of the magnetization components under a generated magnetic field of $b_z = 0.25$ μT. The flip angle θ after application of the RF pulse is given by

$$\theta = \arctan\left[\sqrt{M'^2_x + M'^2_y} \,/\, M'_z\right] \tag{2}$$

Assuming that the sample has a homogeneous T_1 relaxation time and T_2 relaxation time, the signal intensity of images obtained by a spin-echo sequence is given by

$$S(\theta) \propto \frac{\left[1 - 2\exp\left(-\frac{T_R - T_E/2}{T_1}\right) + \exp(-T_R/T_1)\right]\exp(-T_E/T_2)\sin\theta}{1 + \cos\theta \exp(-T_R/T_1)} \tag{3}$$

When the amplitude of the RF pulse is adjusted so that the pulse flips the magnetization to θ = π/2, the signal intensity of an image obtained with an electric current can be normalized by the signal intensity without electric current as

$$g = \frac{S(\theta)}{S(\pi/2)} = \frac{\sin\theta}{1 + \cos\theta \exp(-T_R/T_1)} \tag{4}$$

Figure (c) shows the relationship between the generated magnetic field b_z and the normalized signal intensity g with parameter $T_R/T_1 = 2.0$. This relation allows us to express the intensity of the generated magnetic field $|b_z|$ as a function of the normalized signal intensity g. Thus, distribution of b_z can be experimentally determined from the images obtained with and without electric current and the relation of figure (c).

Experiments and Discussion

The phantom used in measurements consisted of a plastic sphere filled with 1.0 % agarose gel and an insulated wire directed to the x axis. Electric current pulses were applied with an intensity of 100 mA at the timing shown in figure (a). The z component of the generated magnetic field is given by $b_z = (\mu_0 I/2\pi)(\mathbf{r}\cdot\mathbf{j}/|\mathbf{r}|^2)$. Figure (d) shows the distribution of b_z.

Measurements were performed using a 4.7 T MRI system. Images were obtained in a slice perpendicular to the x axis with and without application of electric current. The acquisition parameters were as follows: $T_R = 3000$ ms, $T_E = 60$ ms, slice thickness = 4 mm. The T_1 relaxation time of the agarose gel was measured by an inversion recovery sequence. Figure (e) shows an image obtained with application of electric current. The magnetic field generated by the current caused a decrease in the signal intensity around the wire. The T_1 relaxation time of the agarose gel was 1.5 s. The intensity of the generated magnetic field was calculated and is shown in figure (f). This experimentally determined magnetic field was in good agreement with the theoretically calculated magnetic field.

In conventional methods of electric current detection based on phase images [1,2], phase unwrapping is necessary in the calculation of the magnetic field intensity. If applied electric currents have a complicated distribution, phase unwrapping becomes a complicated procedure. Because the method proposed in this study does not use phase images, phase unwrapping is not required.

References

[1] Joy MLG, Scott GC, Henkelman RM. In vivo detection of applied electric currents by magnetic resonance imaging. Magn Reson Imag 1989;7:89-94.
[2] Scott GC, Joy MLG, Armstrong RL, Henkelman RM. Rotating frame RF current density imaging. Magn Reson Med 1995;33:355-369.
[3] Yamaguchi K, Sekino M, Iriguchi N, Ueno S. Current distribution image of the rat brain using diffusion weighted magnetic resonance imaging. J Appl Phys 2003;93:6739-6741.

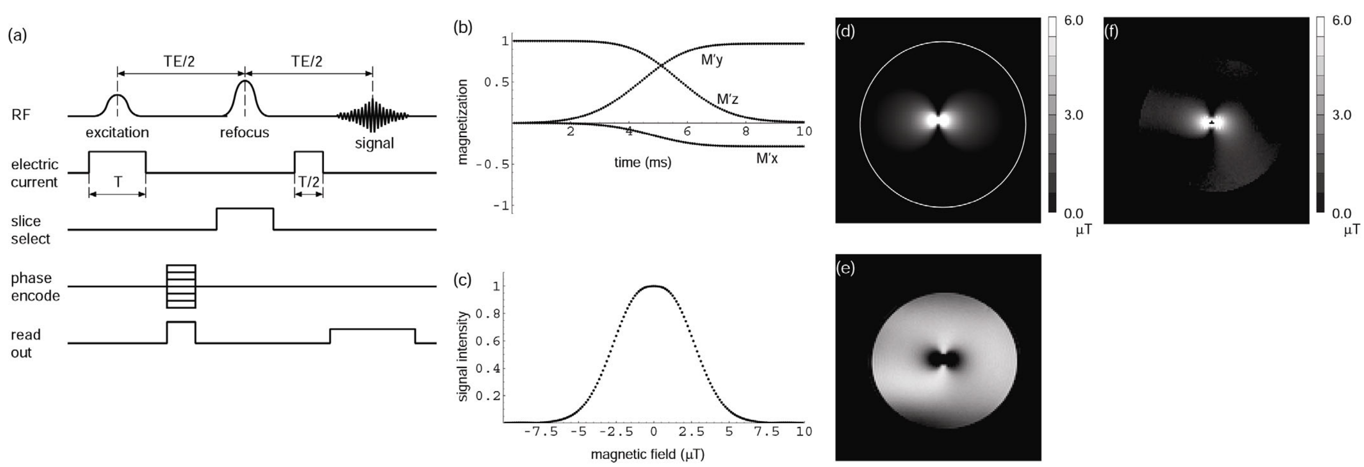

Figure: (a) NMR pulse sequence for detection of electric current. (b) Motions of the magnetization components under a magnetic field of 0.25 μT. (c) Relationship between applied magnetic field b_z and the normalized signal intensity ($T_R/T_1 = 2.0$). (d) Theoretically calculated magnetic field component b_z generated by an electric current of 100 mA. The white circle indicates the edge of the phantom. (e) Image of the phantom with an electric current of 100 mA. (f) Experimentally determined magnetic field component b_z.