Measurement of Nonuniform Current Density by Magnetic Resonance

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***Abstract*—Conventional magnetic resonance imagers can measure the electric current density in any substance which can be imaged by nuclear magnetic resonance. This current density image is created by measuring the magnetic field arising from these currents and taking its curl. These magnetic fields are proportional to the phase component of a complex magnetic resonance image. Measurements of all three components of a quasistatic nonuniform current density in a phantom are described. Expected current density calculations from a numerical solution for the magnetic field which was created by the phantom are presented for comparison. The results of a numerical simulation of the experiment, which used this field solution and which included the effects of slice selection and sampling, are also presented. The experimental and simulated results are quantitatively compared. It is concluded that the principle source of systematic error was the finite slice thickness which causes blurring of boundaries. The method could be used to study the spatial distribution of currents injected by an external source if the currents are repetitive and can be synchronized with the magnetic resonance imaging sequence. Physical rotation of the conducting sample is required.**

I. INTRODUCTION

MANY therapeutic techniques rely on the application of electrical currents to the body, e.g., cardiac defibrillation and pacing, ECT, electrocautery, and numerous treatment methods in physiotherapy. In the field of electrical safety the setting of standards requires knowledge of the currents which result from accidental exposure. Chronic exposure to very small electric and magnetic fields is suspected to have a biological effect. It is therefore relevant to seek methods for the measurement of applied electric currents in tissue. Presently, there is no non-invasive way to do this. A noninvasive current measurement technique and its application to measure a non-uniform current density is described. It could be used to measure applied (i.e., nonbiological) currents. Such currents must be repetitive and synchronized with the magnetic resonance imaging sequence. Physical rotation of the conducting sample is required.

Proposed methods for noninvasive measurement of currents usually involve mapping the magnetic fields outside the current carrying region (for example, with a SQUID magnetometer) [1]–[5] or, alternatively a magneto-acoustic method [6]. Methods of the first type yield a nonunique result unless assumptions such as planar current distributions or dipole sources are made. The method described in this paper requires no assumptions as to the spatial distribution of the current.

Nuclear magnetic resonance imaging can be used to compute the current density $\vec{J}$ in liquids or gels [7]–[12], [5]. The only requirement is that the medium carrying the current can be imaged. To measure the current density $\vec{J}$ one first measures the incremental phase Φ of a conventional magnetic resonance image with the current flowing. This phase is proportional to the magnetic flux density $\vec{B}$ which is caused by the current density. Ideally,

$$\Phi \propto B_j = \vec{B} \cdot \frac{\vec{B}_0}{|B_0|} \tag{1}$$

where B_j is the component of $\vec{B}$ parallel to the main imaging field $\vec{B}_0$. The current density can then be found using the static version of Maxwell's equations [13] and the constituent equations. In the static assumption, the displacement current, $\partial\vec{D}/\partial t$, and magnetic induction, $\partial\vec{B}/\partial t$, are negligible. Therefore,

$$\vec{J} = \nabla \times \vec{B}/\mu, \tag{2}$$

and the current density $\vec{J}$ can be determined if $\vec{B}$ and μ are known. Since the materials imaged by magnetic resonance generally have low magnetic susceptibility ($< 10^{-5}$), μ may be replaced by μ_0 in (2).

In a previous paper, the measurement of a single component of a uniform $\vec{J}$ which was perpendicular to a single axial slice through a cylindrical phantom was reported [9]. Here the measurement of all three components of $\vec{J}$ in a phantom with a nonuniform current density is reported. Since components of $\vec{J}$ lying in the plane of the magnetic resonance image were desired, derivatives of $\vec{B}$ perpendicular to this plane had to be measured. Three different methods for measuring these normal derivatives are compared.

Manuscript received September 24, 1990; revised February 4, 1991. This work was supported by the Medical Research Council of Canada, the National Science and Engineering Research Council of Canada, and the General Electric Medical Systems of Canada.

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IEEE Log Number 9100171.

In Section II (Materials and Methods) we describe the phantom, the current imaging pulse sequence, and the postprocessing. Included in the postprocessing are checks on the measured magnetic fields to verify their consistency with the static version of Maxwell's equations. The magnetic field that should have been produced by our apparatus was solved by finite differences. This solution allowed the simulation of the experimental current density formation including the effects of the finite slice thicknesses. The expected current density in the phantom was also computed from the magnetic field solution. The expected current density and the simulated images are compared, in Section III, with the actual images to demonstrate the systematic errors in the measurement and to determine their origin. Consistency checks on the measured magnetic fields are also presented in Section III.

II. MATERIALS AND METHODS

A. The Phantom

The phantom is shown schematically in Fig. 1. It was cylindrically symmetric and consisted of two copper disc electrodes of radius 9.5 mm and thickness 1.6 mm, set at either end of a lucite cylinder, 50.8 mm in height and 50.8 mm in diameter. At the center of the cavity was set an insulating spherical shell (a ping-pong ball) 0.5 mm thick and 37.6 mm in outside diameter. This shell was filled (through a single hole) with $CuSO_4$ doped saline solution (0.9 g/dl NaCl, 0.1 g/dl $CuSO_4.5H_2O$, T_1 = 340 ms, T_2 = 275 ms). The spherical shell was held in place by hollow posts 2 mm in diameter as shown in Fig. 1. The wires which carried the electric current to the electrodes were held in fixed positions with respect to the cell as shown in Fig. 1 and were twisted together as they approached the cell to produce a negligible magnetic source.

B. Imaging Sequence

The magnetic resonance imaging was performed with a General Electric CSI 2 Tesla, 30 cm bore, MR scanner. The current imaging pulse sequence of Fig. 2 was a standard 3-D slab select or 2-D spin echo sequence with the addition of a bipolar current pulse. The readout gradient was 320 Hz/mm and 128 samples of the echo were acquired. The field of view was 65 mm in the slice yielding a pixel separation of 0.52 mm. The repetition period (TR) was 900 ms and the echo time (TE) was 115 ms. The current pulses were 30 mA each with a duration of 50 ms (I = 30 mA, T_c = 100 ms, see Fig. 2).

The current pulse was bipolar so that the phase shifts which it produced were not canceled out by the nonselective 180° pulse. Excitations with a positive/negative current waveform and those with a negative/positive waveform were interleaved to allow compensation for any drift in the imager. Data sets for the $\pm$ and $\mp$ current polarities remained separate.

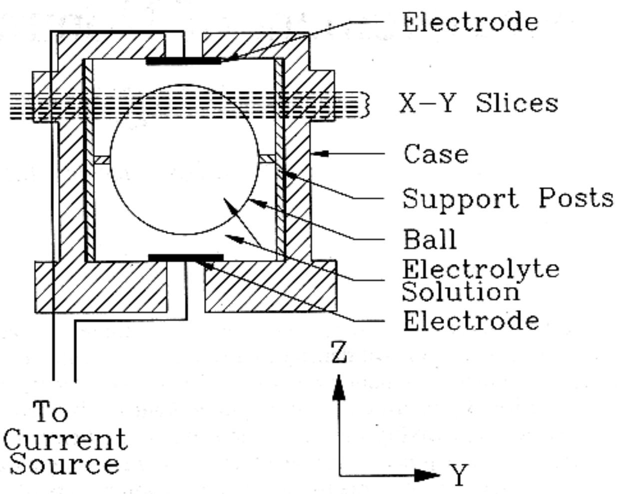

Fig. 1. The "phantom" which was imaged, drawn roughly to scale. The *Case* was a cylinder with copper *Electrodes* at either end and a *Ping-Pong Ball* suspended in the center. The *Ping-Pong Ball* is held in place by two Horizontal *Supports* which are attached to two of four vertical *Supports*. An electric *Current Source* causes currents to flow through the *Electrolyte Solution* and around the *Ball*. Both the cylinder and the *Ball* are filled with electrolyte, however, since the shell of the *Ball* is an insulator, no current flows inside it. Magnetic field images were made for six *X-Y Slices* shown. This allowed current density images to be computed for the central four *Slices*.

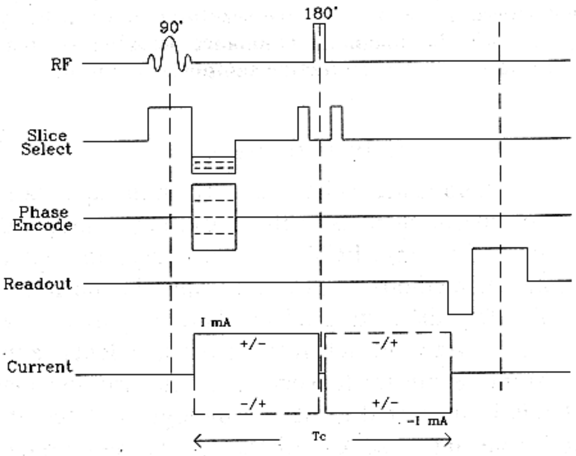

Fig. 2. The current density imaging sequence.

To obtain the components of $\vec{J}$ which lie in the tomographic plane one must take derivatives of the magnetic field in a direction perpendicular to the slice. Three different slice selection strategies were employed for this purpose. In all three strategies, six slices were obtained with a separation (center to center) of 1.25 mm and offset from the equator from 10.7 to 16.95 mm (see Fig. 1). In the "thin-slice" strategy the slice thickness was also 1.25 mm and was obtained using a 90° pulse with a "sinc" envelope with one sidelobe. In the "overlapping-slice" strategy the slices were 3 mm thick and the envelope had 2 side lobes. In both these strategies adjacent slices were obtained in separate sequences to avoid slice interference. In the "three-dimensional phase encode" strategy, a single slab was selected and subdivided into 8 subslices by phase encoding in the slice selection direction. The slice