Detection of Reentry Currents in Atrial Flutter by Magnetocardiography

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Abstract—**We discuss the use of magnetocardiography to detect reentry currents in cardiac flutter and fibrillation. The magnetic field produced by induced atrial flutter was measured in isolated rabbit hearts. A moving dipole model is proposed to treat the experimental data and to locate the reentry path.**

Introduction

An interesting challenge in the study of biomagnetism is the identification of the electric source pattern by measuring the associated magnetic field. This is the so-called inverse problem. A solution to the inverse problem has been pursued but found only in a few cases, such as the localization of brain activity related to evoked fields [1] and epileptic foci [2], and His bundle activity in cardiomagnetism [3].

In these studies, a simple model for the electric source was assumed, namely the current dipole. For extended sources, like those present in cardiomagnetism, this model is not adequate and has been replaced by the *equivalent* current dipole concept. Although this approximate solution fails to describe adequately the normal sinus rhythm [4], [5] it could be a good description for the abnormal depolarization associated with sustained arrhythmias like cardiac flutter and fibrillation.

These arrhythmias have been known for a long time. However, some doubt persists about the exact electrical behavior associated with them. Different hypotheses have been proposed. Atrial flutter, for instance, is usually explained by the existence of a circus movement (reentry current) involving a large part of the atria (macroreentry); the existence of an ectopic focus of abnormal impulse formation is still considered as a possible mechanism for this arrhythmia [6]. Some forms of flutter induced in animals have even been explained by the existence of a small scale variant denoted microreentry [7]. Electrical potential mappings, using invasive electrodes in animals have proven the existence of a reentry mechanism [8]. Nevertheless, the differences among animal species preclude the extrapolation of these results to man [9].

The mechanism of atrial fibrillation is even more uncertain. Many of its characteristics are compatible with the reentry of multiple activation fronts. Another possible mechanism is that of disordered automaticity [10]. Although fibrillation is a more basic and general problem than flutter, the constant periodicity of flutter should make its observation easier. In fact, the ECG *F* waves associated with flutter show a consistent pattern over a wide spectrum of patients [9].

The development of a noninvasive technique for studying these arrhythmias could be important for the investigation of human patients. In this paper, we propose to explore the capabilities of the MCG in detecting reentry or circus movement current patterns associated with these kinds of arrhythmias. Preliminary results on the detection of magnetic *F* waves were reported previously [11].

Isofield Maps

Assuming the existence of a reentry current, at a given instant of time, the source of magnetic field can be described by an equivalent current dipole, producing the well known dipolar isofield map. These maps are constructed from recordings of the magnetic field as a function of time at different positions over the source. Usually only the z (or vertical) component of the field is measured over a planar and rectangular grid. From this one obtains the function $B(x_i, y_i, t)$ or $B_i(t)$, which contains the vertical components of the magnetic field at time t, and the rectangular coordinates x_i and y_i of the point i of a grid of n points. The n functions $B_i(t)$ are measured, while the electric potential $V_o(t)$ is recorded at a fixed position. The recording of $V_o(t)$ is used as a time base to correlate all the measured $B_i(t)$, thus enabling the construction of a n-dimension vector that partially describes the "state" of the magnetic field

$$[B(t_j)] = [B_1(t_j), B_2(t_j), \cdots, B_n(t_j)] \quad (1)$$

for different discrete instants of time t_j. Each of these vectors is usually represented by a map where the associated $B_i(t_j)$ values are interpolated by spline functions to obtain isofield contour lines at one instant of time. If the successive isofield maps obtained are dipolar, the position of the equivalent current dipole can be located and its motion

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monitored, enabling one to follow the depolarization wavefront around the reentry path. This kind of measurement has already been shown to be feasible with rabbit atrial tissue experiments where the normal sinus depolarization has been monitored by following the evolution of the dipolar isofield maps [12].

An important fact to consider is the precision with which the inverse problem can be solved from knowledge of the n-dimension vector $[\boldsymbol{B}(t_j)]$. The usual procedure consists of solving the direct problem (Biot–Savart law) by an iterative method. This is the so called moving dipole solution or dipole location method [13]. With such an approach, depending on the noise level and other parameters, there remains an uncertainty of the order of several millimeters in the localization of the dipole position [13]–[15]. This could be a limitation when trying to determine the size of a small reentry circuit.

A Simple Model and the Isoamplitude Map

There are reports presenting evidence for a two-dimensional circular surface as the actual reentrant structure in atrial flutter [16]. Nevertheless let us assume, for simplicity, the classic one-dimensional model of circus motion, with only one path length and a uniform conduction velocity. Let us also assume a homogeneous depolarization process (as opposed to an axial one) [12] and neglect contributions from volume conductor currents.

The reentry current can be represented by a current dipole $\boldsymbol{p}$ moving around a circle (see Fig. 1). The electrical potential at point $\boldsymbol{r}$, at a given instant of time, with the dipole at point $\boldsymbol{r}'$ is given by

$$V'(r) = \frac{1}{4\pi\sigma} \frac{\boldsymbol{p} \cdot (\boldsymbol{r} - \boldsymbol{r}')}{|\boldsymbol{r} - \boldsymbol{r}'|^3}. \tag{2}$$

where σ is the electric conductivity of the medium. Similarly, the magnetic field is given by

$$\boldsymbol{B}(r) = \frac{\mu_0}{4\pi} \frac{\boldsymbol{p} \times (\boldsymbol{r} - \boldsymbol{r}')}{|\boldsymbol{r} - \boldsymbol{r}'|^3} \tag{3}$$

where μ_0 is the magnetic permeability (a constant quantity in the body).

Let x measure the distance along a line from the circle center to the dipole when $\alpha = 0$ where α is the angle describing the dipole positions moving along a circular path (Fig. 1). Let the z direction be perpendicular to the plane of the circle, and the y direction be perpendicular to x and z. If the potential is measured along the line $y = 0$ when $z = d$, (2) can be rewritten as

$$V(\boldsymbol{r}) = \frac{1}{4\pi\sigma} p \frac{r_0 \sin \alpha}{(R^2 + r_0^2 + d^2 - 2Rr_0 \cos \alpha)^{3/2}} \tag{4}$$

where R is the radius of the circle and r_0 is the distance between the center of the circle, taken as the origin, and the projection of the observation point r into the plane of the circle. Similarly, the z component of the magnetic field

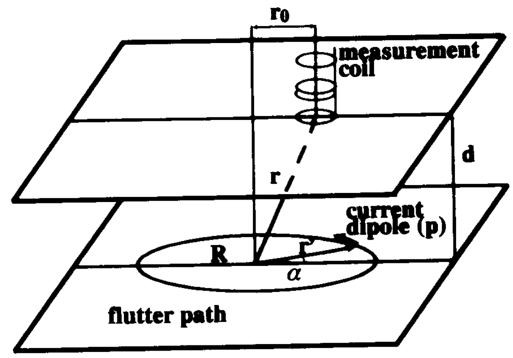

Fig. 1. A simple one dimensional model for the reentry current. A current dipole of constant intensity p is moving around a circle of radius R. The dipole is at r' making an angle α with the x axis. The plane of measurement is parallel to the circuit plane, at a distance d from it. The measuring position is at r; r_0 is its projection on the circuit plane.

can be written in terms of the same variables as

$$B(\boldsymbol{r}) = \frac{\mu_0}{4\pi} p \frac{(R - r_0 \cos \alpha)}{(R^2 + r_0^2 + d^2 - 2Rr_0 \cos \alpha)^{3/2}}. \tag{5}$$

Fig. 2(a) and (b) show a succession of curves representing the instantaneous electrical potential and the magnetic field as a function of time (or α), taken respectively from (4) and (5) for a measurement at a given height and for different distances from the circle's center. It is interesting to note that while the mean or dc value (resulting from integration during a period) of the electric potential is zero [Fig. 2(a)], this is not so for the magnetic field [Fig. 2(b)]. This result is to be expected since (5) is an odd function of α.

However, the possibility of observing experimentally this dc component can be masked by the repolarization current. Indeed, in spite of its smaller value, as compared with the depolarization current, the time integral of the two should be equal (due to the conservation of charge). The repolarization current has been detected magnetically in nerves [17] and shown to be in opposite direction to the depolarization current. The same opposition has been observed between depolarization and repolarization of the cardiac P wave by magnetocardiographic measurements [18], [19].

Nevertheless, the amplitude of the ac magnetic field generated by this model also depends on the position of the measurements. This enables the localization of the center and also the determination of the size of the reentry circuit. Indeed, it is easily seen that the amplitude of the oscillatory field (magnetic F waves) changes from zero to a maximum and returns again to zero when r_0 is increased.

Fig. 3(a) shows the amplitude of the ac component of magnetic F waves as a function of the distance from the center of the circuit, for a circuit of 0.5-cm radius and for different values of the finite area of the gradiometer pickup coil. The amplitude is *zero* above the center of the circuit independent of the gradiometer pickup coil size, because of the cylindrical symmetry.

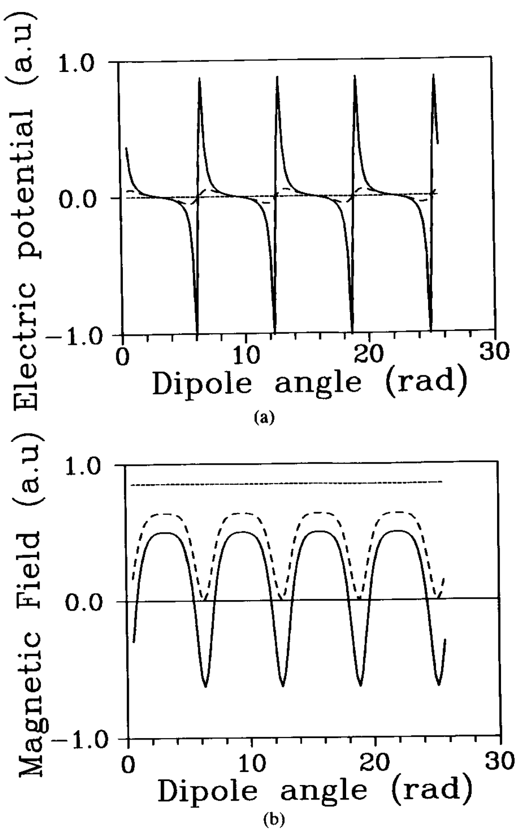

Fig. 2. (a) Electric potential produced by the moving current dipole and calculated at a distance d = 0.2 cm over the circle's center (r_0 = 0, dotted line, r_0 = 1 cm, dashed line; r_0 = 1.5 cm, continuous line), assuming a circle of radius R = 1 cm. (b) The component of the magnetic field perpendicular to the circle plane calculated at the same positions as above, but with a distance of d = 1.5 cm.

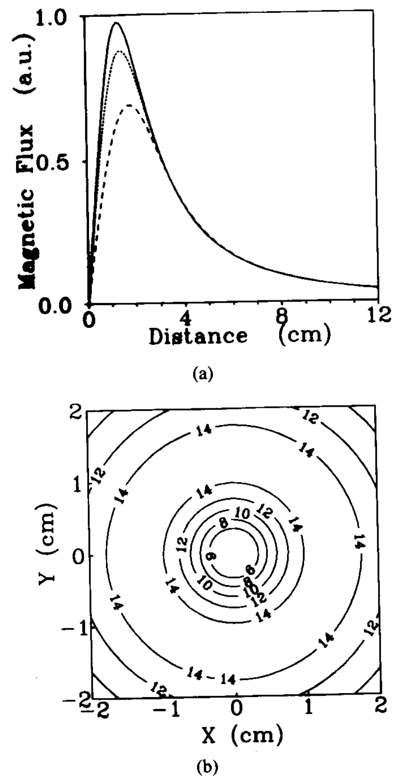

Fig. 3. (a) Amplitude of the magnetic F waves as a function of the distance r_0, for R = 0.5 cm, assuming different radius for the pickup coil (0.10 cm, continuous line; 0.75 cm, dotted line; 1.5 cm, dashed line). (b) Isoamplitude map of the ac component of the magnetic field perpendicular to the circle plane, calculated over a grid of 4 × 4 cm.

Fig. 3(b) is an extension to two dimensions of the results in the preceding figure and shows the isoamplitude map of the magnetic F waves. It has an axis of symmetry of rotation due to the circular path and a central point of zero magnetic field. Using this simple model, we can identify and locate the existence of a reentry path by the presence of zero amplitude of the ac magnetic component.

Such an isoamplitude plot is a single map for the whole experiment. Once the $B_i(t)$ functions have been measured, at the n grid positions, it is possible to associate each of the n points to the corresponding peak-to-peak amplitude of the magnetic periodic signal $\Delta B_i(t)$ and to obtain the vector $[\Delta B] = [\Delta B_1, \Delta B_2, \cdots \Delta B_n]$. As in the case of the isofield maps, these discrete n values can be interpolated by spline functions and the isoamplitude lines can be plotted.

Materials and Methods

The experiments were performed on isolated rabbit hearts. The hearts were extracted from the thorax by a simple surgical technique, following decerebration of the animal. They were maintained in perfusion (Langerdorf's system) with a tyrode solution (NaCl, glucose, $NaHCO_3$, KCL, NaH_2PO_4, $MgCl_2$ and $CaCl_2$), bubbled with carbogen (95% O_2 and 5% CO_2). The isolated heart was immersed in a 900 cm^2 surface beaker containing the solution to avoid volume currents contributions to the magnetic field [20].

While perfusing the heart with a tyrode solution containing acetylcholine (0.4 mg/l − 22 × 10^{-7} molar), pacing was induced by an electric stimulator [6] delivering pulses at a frequency of 20 Hz, duration of 3 ms and 20 V/A in amplitude. Atrial flutter was easiest to induce in the region covered by the right atrial appendage. The rapid rhythm could be easily interrupted by stopping the supply of acetylcholine. This procedure leads to the return of the normal electrical activity of the heart, and the tachyarrythmia can be induced repeatedly. Such an experimental procedure does not require the presence of anatomical obstacles, such as caval openings or myocardial lesions, for the flutter to take place. Our method usually leads to a rapid and repetitive atrial activity that is less regular than that obtained using other procedures [7], [16].

Electrical measurements were performed using glass extracellular electrodes immersed in the solution. One of the electrodes was positioned near the right atrial tissue; hence that record is very similar to the electrogram.

The experimental study was carried out by using a onechannel MCG system, performing successive measurements. A SQUID was coupled to a second order gradiometer having the following specifications: 4, −8, 4 turns with 1.5 cm diameter and a 4 cm base line, having a sensitivity of $50\, fT/\sqrt{Hz}$. The attenuation of a uniform field was better than 100 dB in the z direction and better than 80 dB in the x and y directions. No external magnetic shielding was used.

The magnetic signals were recorded as a function of time over a square grid centered on the isolated heart. The approximate distance from the lower gradiometer coil to the tissue surface was 1.5 cm. The electric and magnetic signals were recorded on a FM tape recorder (HP, model 3964A), and filtered by a commercial filter (Wavetek, model 852) using 0.5–100 Hz bandwidth. The signals were digitized and processed using a computer program and the segments corresponding to the ventricular depolarization (*QRS* complex) were exclused after visual inspection. The signals were then digitally filtered using a 3–20 Hz bandwidth. This bandwidth was chosen according to the frequency of the flutter when observed on a spectrum analyzer (HP, model 3582A). The frequency of the flutter was determined through the spectral analysis of the signals identifying the peak frequency common to both electric and magnetic signals.

The equivalent dipoles were calculated from the isofield maps by using a moving dipole solution [13]. The reentry current circle was calculated from the isoamplitude map with a least-squares-fit program. The fitness was evaluated by the factor $\mathfrak{F}$ defined by Erne *et al.* [18] as

$$\mathfrak{F} = \frac{\sqrt{1/N \sum_{i=1}^{N} (D_i - B_i)^2}}{B_{max} - B_{min}} \qquad (6)$$

where D_i are the magnetic fields produced by the simulated dipole at the grid point i, B_i are the measured experimental fields, and B_{max} and B_{min} are the maximum and minimum measured values.

Results and Discussion

Fig. 4 shows a typical magnetic and electric recording of the F wave obtained by using the procedure described above. In the twelve experiments performed the frequency of atrial flutter waves was usually between 7 and 12 Hz with a pattern characterized by atrioventricular block having 8 or more F waves between *QRS* complexes.

A. Isofield Maps

The frequency of flutter was usually not constant, varying about 20% between the beginning and the end of a session. To overcome this problem the electrical signal, which was recorded at a fixed position throughout the experiment, was not used as a time reference but as a phase reference. For each point of the grid the magnetic signal recorded as a function of time provides a discrete number of magnetic field values taken at given phases of the electric signal. The isofield maps were then calculated. Dipolar configurations were obtained during a large part of the total flutter period confirming the possibility of describing the depolarization process by an equivalent current dipole.

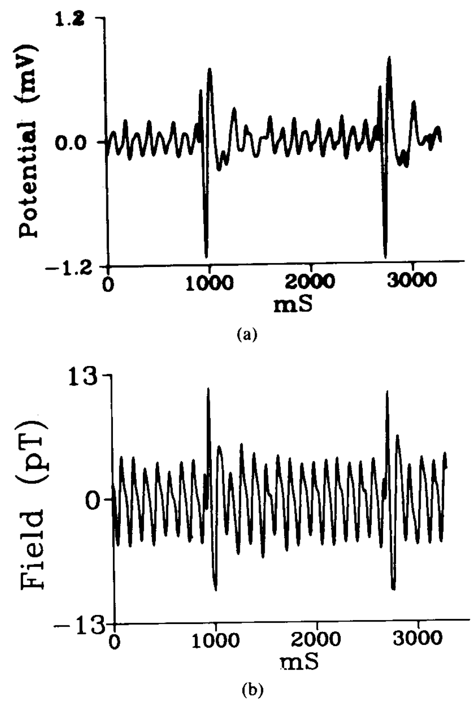

Fig. 4. Typical electric and magnetic recording of the F waves with a severe degree of AV block.

In most of the experiments, the sustained flutter did not last long enough to enable the recording of a complete measurement grid. Three flutter episodes persisted for about 1 h, and the magnetic field maps showed the same pattern in each case. Fig. 5 shows typical isofield maps calculated at two successive phases of the flutter cycle separated by one half of a period (0.5 T). In spite of the large number of measurements involved in each experiment, the magnetic field was usually not mapped completely before the flutter terminated. Nevertheless, the results already obtained enable us to draw some general conclusions. Polarity inversion of the dipolar patterns corresponding to the inversion of the equivalent dipole can be attributed to the circular motion of the reentry current. However, the inversion of polarity is not by itself proof of the existence of the reentry circuit since such behavior is also present in the normal P wave and attributed to the current inversion between depolarization and repolarization [18], [19].

The positions of the equivalent dipoles, calculated from the isofield maps for different phases of the quasi-periodic signal, are all localized inside a region of about 0.5 cm diameter, but do not follow a closed path. As mentioned earlier, the isofield maps with the moving dipole solution are not capable of locating the position of the equivalent

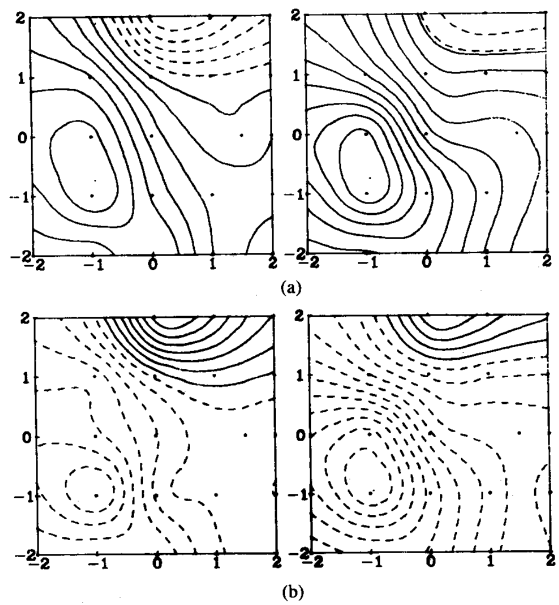

Fig. 5. Isofield maps calculated at four successive phases of the flutter cycle (T): $0.2T$, $0.3T$ (a); $0.7T$ and $0.8T$ (b).

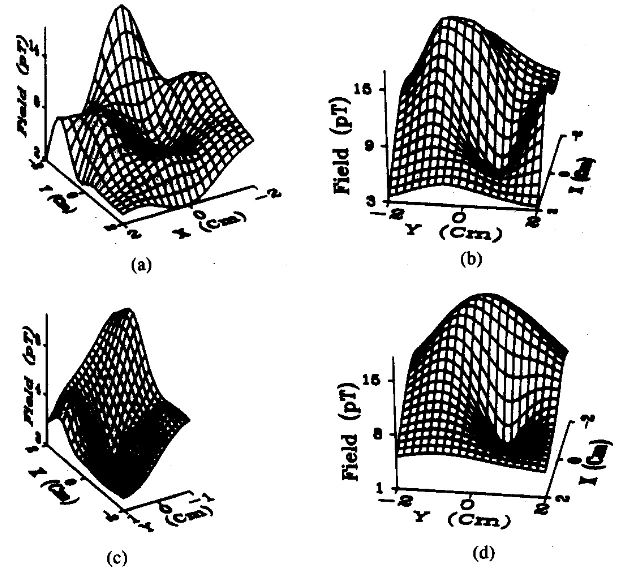

Fig. 6. Three-dimensional representation for the amplitude of the magnetic F waves for three different episodes of flutter are shown in (a), (b), and (c). A best fit to the experimental result of (b), with the circular path tilted by an angle of 23° can be seen in (d)

dipole with a precision better than a few millimeters. It is difficult to obtain the exact path of the reentry circuit using isofield maps.

B. Isoamplitude Maps

Fig. 6(a)–(c) show in a three-dimensional representation, the amplitude of the magnetic F waves of three flutter episodes. Although there is no axis of symmetry of rotation, such as in Fig. 3(b), there is a point of near zero minimum amplitude. This minimum is located above the atrium's position which is compatible with the reentry current mechanism.

Fig. 7(a) shows the isoamplitude map of the ac component of the magnetic F waves obtained in one of the long sustained episodes corresponding to Fig. 6(b). The lack of cylindrical symmetry of the experimental data can be interpreted by assuming a nonuniform amount of excited tissue around the reentry path, as usually found by invasive electrodes measurements [6]. Such a lack of symmetry can also be partially explained by tilting the plane of the reentry circuit with respect to the measurement plane. Figs. 6(d) and 7(b) show, as an example, the best fit to the experimental results of Figs. 6(b) and 7(a) obtained with a current dipole of $p = 50$ nA · m moving around a circle of $R = 0.46$ cm, centered at a point having coordinates $X = -0.6$ cm, $Y = 0.27$ cm and $Z = 1.75$ cm of the grid and tilted by an angle of $\theta = 23°$ with respect to the measurement plane. The factor $\mathfrak{F}$ of (6) has been minimized to about 10%. Results presented in Fig. 6(a) and (c) can also be fitted with a value for $\mathfrak{F}$ of 25% and 15%, respectively. All the three fitting results are presented in Table I. This seems to indicate that the circular motion of a current dipole is a good zero order approxi-

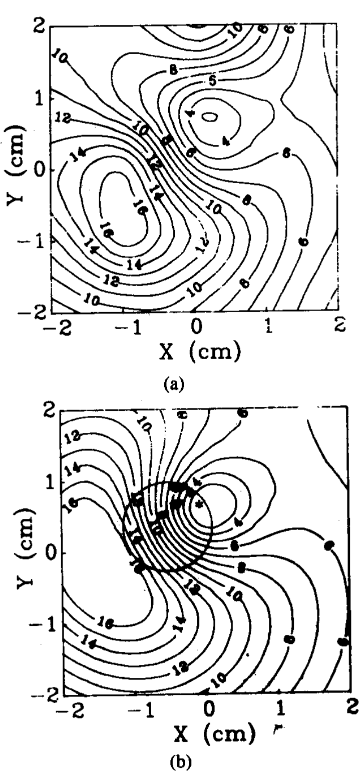

Fig. 7. (a) Isoamplitude map of the vertical component of the magnetic field obtained in one of the persistent flutter episodes. (b) The best fit was obtained assuming that the reentry circuit has a radius of 0.46 cm and is tilted by an angle of 23°. The continuous circular line represents the circuit and the stars stand for the position of the equivalent current dipoles representing the best fit to the isofield maps corresponding to six different instants of time (two of them are superposed).

TABLE I
BEST FIT PARAMETERS FOR THE THREE FLUTTER EPISODES CORRESPONDING TO Fig. 6(a), (b) and (c)

Flutter Episode	R (cm)	θ (deg)	X (cm)	Y (cm)	Z (cm)	P (nA · m)	$\mathfrak{F}$ (%)
a	0.50	29	−0.23	0.52	1.80	30	25.5
b	0.46	23	−0.61	0.27	1.75	50	10.8
c	0.30	43	−0.52	0.75	1.30	145	15.2

mation for the reentry current obtained with the described experimental procedure used to produce the flutter.

The advantage of the isoamplitude map of the ac component is that it is independent of the flutter frequency. Even if the frequency changes during the experiment, as was observed due to changes in either propagation speed or path length, the plot displays a near zero value above the heart. Another advantage of such a plot is that the signal obtained at a given grid position is already proportional to the difference of the signals produced by the equivalent dipole at two different dipole positions, giving information about the size of the circuit.

V. CONCLUSION

The magnetic signal produced by atrial flutter induced in isolated rabbit hearts was detected. A simple model describing a circus reentry path has been discussed and fitted to the experimental data. Agreement between the simulated magnetic field obtained using the model and animal experimental results suggests that, at least in the preparation used, the presence of a reentry current can be checked and described in a zero-order approximation by the circular motion of a constant intensity current dipole. It appears that magnetocardiography can be used as a noninvasive technique to locate and to provide information about the radius of the circuit of such reentry currents.

Our primary objective was the detection of the presence of a circus movement in atrial flutter. It is instructive to point out the possibility of localizing the reentry circuit with its physiological and clinical implications. The possibility of carrying out studies in humans, or in isolated animal hearts, presents some difficulties since the atrial contribution should be discriminated from the contribution of ventricular activity. The existence of volume currents, while not considered in our study, will also contribute to some extent and could deteriorate the results.

Using the same model, reentry currents during atrial fibrilation could possibly be detected by using multichannel systems, measuring the instantaneous magnetic field at different positions in space without having to displace the detecting array [14].

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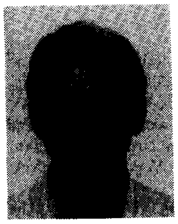
REFERENCES

[1] S. J. Williamson and L. Kaufman, "Magnetic field of the cerebral cortex," in *Biomagnetism*, S. N. Erne, H. D. Hahlbohm, H. Lubbig, Eds. Berlin: Walter and Gruyer, 1981, pp. 353–402.
[2] G. B. Ricci, G. L. Romani, I. Modena, S. Barbanera, R. Leoni, and P. Carelli, "Meg and EEG measurements and their correlation in man, preliminary observation," *Electroenceph, clin. Neurophysiol.*, vol. 52, pp. 95–102, 1981.
[3] J. L. Patrick, D. W. Hess, J. H. Tripp, and D. E. Farrell, "The magnetic field produced by the conduction system of the human heart," *Il Nuovo Cimento*, vol. 2D, pp. 255–265, 1983.
[4] R. S. Gonelli and M. Agnello, "Inverse problem solution in cardiomagnetism using a current multipole expansion of the primary sources," *Phys. Med. Biol.*, vol. 32, pp. 133–142, 1987.
[5] J. C. Campos, U. Tachinardi, C. P. Melo, and P. Costa Ribeiro, "Depolarization direction in a multiple dipole model for the direct problem in magnetocardiography," in *Biomagnetism'76*, K. Atsumi, M. Kotani, S. Ueno, T. Katila and S. J. Williamson, Eds. Tokyo: Tokyo Denky University, 1987, pp. 306–309.
[6] M. A. Allessie, W. J. E. P. Lammer, and I. M. Bonke, "Intratrial reentry as a mechanism for atrial flutter induced by acetylcholine and rapid pacing in the dog," *Circulation*, vol. 70, pp. 123–125, 1984.
[7] J. P. Boineau, A. C. Wylds, L. J. Autry, R. B. Schuessler, and C. B. Miller, "Mechanism of atrial flutter as determined from spontaneous and experimental models," in *Tachycardias: Mechanisms, Diagnosis, Treatment*, M. E. Josephson and J. J. Weellens, Eds. Phyladelphya: Lea and Febiger, 1984, pp. 91–111.
[8] F. G. Cosio, F. Arribas, J. Palacios, J. Tascon, and M. Lopez-Gil, "Fragmented Electrograms and continuous electrical activity in atrial flutter," *Amer. J. Cardiol.*, vol. 57, pp. 1309–1314, 1986.
[9] L. B. Frame, R. L. Page, and B. F. Hoffman, "Atrial reentry around an anatomic barrier with a partially refractory excitable gap," *Circ. Res.*, vol. 58, pp. 495–511, 1986.
[10] J. A. Abildskov, K. Millar, and M. J. Burguess, "Atrial fibrillation," *Amer. J. Cardiol.*, vol. 28, pp. 263–267, 1971.
[11] P. Costa Ribeiro, A. C. Bruno, E. Parente Ribeiro, J. S. do Carmo, E. Costa Monteiro, and A. Fonseca Costa, "Detection of magnetic atrial flutter waves in isolated rabbit hearts," in *Advances on Biomagnetism*, S. J. Williamson, M. Hoke, G. Stroink, and M. Kotani, Eds. New York: Plenum, 1990, pp. 389–392.
[12] E. Costa Monteiro, S. W. Louro, A. C. Bruno, A. Fonseca Costa, and P. Costa Ribeiro, "Detection of oblique wave front depolarization by means of magnetic field measurements," in *Biomagnetism '87*, K. Atsumi, M. Kotani, S. Ueno, T. Katila and S. J. Williamson, Eds. Tokyo: Tokyo Denky University, 1987, pp. 310–313.
[13] B. Neil Cuffin, "Effects of measurement errors and noise on MDG moving dipole inverse solution," *IEEE Trans. Biomed. Eng.*, vol. BME-33, pp. 854–861, 1986.
[14] P. Costa Ribeiro, S. J. Williamson, and L. Kaufman, "SQUIDs arrays for simultaneous magnetic measurements: Calibration and source localization performance," *IEEE Trans. Biomed. Eng.*, vol. 35, pp. 551–560, 1988.
[15] E. Costa Monteiro, A. C. Bruno, S. R. W. Louro, P. Costa Ribeiro, and A. Fonseca Costa, "Magnetic localization of a current dipole implanted in dogs," *Phys. Med. Biol.*, vol. 32, pp. 65–70, 1987.
[16] J. P. Boineau, "Atrial flutter, a synthesis of concepts," *Circulation*, vol. 72, pp. 249–257, 1985.
[17] J. P. Wikswo, J. P. Barach, and J. A. Freeman, "Magnetic field of a nerve impulse: First measurements," *Science*, vol. 208, pp. 53–55, 1980.
[18] S. N. Erne, R. R. Fenici, H. D. Hahlbohm, J. Korsukewitz, H. P. Lehman, and Y. Uchikawa, "Magnetographic study of the PR segment of normals," in *Biomagnetism: Application and Theory*, H. Weinberg, G. Stroink, and T. Katila, Eds. New York: Pergamon, 1985, pp. 134–136.
[19] R. R. Fenici, M. Masselli, S. N. Erne, and H. D. Hahlbohm, "Magnetocardiographic mapping of the P-R interval phenomena in an unshielded Hospital Laboratory," *Biomagnetism: Application and Theory*, H. Weinberg, G. Stroink, and T. Katila, Eds. New York: Pergamon, 1985, pp. 137–141.
[20] I. R. Eghrari, E. Costa Monteiro, P. Costa Ribeiro, J. P. von der Weid, P. M. Oliveira, and A. Paes de Carvalho, "On the influence of the volume conductor in magnetocardiography: an experimental approach," *Il Nuovo Cimento*, vol. 2D, pp. 346–355, 1983.



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He was Research Engineer in the Department of Physics at PUC, Rio. He joined the Istituto di Elettronica dello Stato Solido, Consiglio Nazionale delle Richerche, Rome, Italy, as an International Center for Theoretical Physics Fellow in 1987–1988. He is currently a Post Doctoral Fellow in the Department of Physics at New York University, New York, NY. He received the Pew Foundation Latin American Award in 1990. His research interests involve SQUID based instrumentation and modeling, and scientific visualization of biomagnetic signals.

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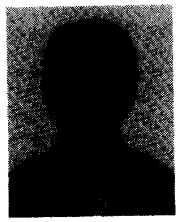
He worked for two years in the Department of Physics of the Pontificia Universidade Católica, Rio de Janeiro, beginning in 1989 with a CNPq fellowship. His research dealt with computer simulations and modeling of the flutter phenomena. He intends to pursue the M.Sc. degree in computer sciences at an american institution.



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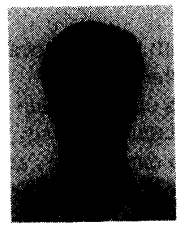
He began working in the Department of Physics of Pontificia Universidade Católica, Rio de Janeiro, in 1989 with a CNPq fellowship. He is currently working on computer simulations of heart activity, and in magnetic localization of small objects in human bodies.



Eduardo Parente Ribeiro was born in Rio de Janeiro, RJ, Brasil in 1967. He received the B.S. degree in electrical engineering from Pontificia Universidade Católica (PUC), Rio, RJ, Brasil in 1990, and the M.Sc. degree in Electrical Engineering in 1992.

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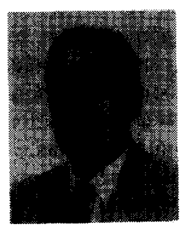
Elisabeth Costa Monteiro received the M.D. degree from Federal University of Rio de Janeiro, Brazil, in 1983 and specialized in Internal medicine in 1984. She received the Master of Science degree in 1988 and received the Ph.D. degree in biophysics in 1992 from the Carlos Chagas Filho Biophysics Institute, Federal University of Rio de Janeiro.

Since 1983 she has been working at the Department of Physics of the Pontificia Universidade Católica of Rio de Janeiro as a researcher in joint projects in the area of Biomagnetism. Her research interests include detection of Biomagnetic fields and cardiac electrophysiology, specially electrophysiologic mechanisms of arrythmias.



Ayres Fonseca-Costa was born in Rio de Janeiro, Brazil. He graduated from Medical School at the Federal University of Rio de Janeiro (UFRJ) in 1955 and did post-graduate work at the Mayo Clinic and at Tulane University in 1960–1961. In 1970 he received the degree as Free Professor of Physiology at the Biomedical Institute of the UFRJ. He has been a faculty member of the UFRJ from 1958 until retirement in 1988.

Currently he is Emeritus Head of the Hemodynamics Laboratory, Carlos Chagas Filho Biophysics Institute, UFRJ.