A Model for Predicting Electromagnetic Interference of Implanted Cardiac Pacemakers by Mobile Telephones

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***Abstract*—A prediction of the electromagnetic interference (EMI) of pacemakers due to mobile phones is significant in improving the immunity of pacemakers. The Pacemaker Committee of Japan recently conducted immunity tests of pacemakers for mobile phones, and consequently concluded that the connector between the pacemaker housing and the lead wire of the electrode plays a major role for the EMI due to mobile phones. Based on this finding, a computer model for predicting the EMI level has been presented, in which the internal impedance seen from the connector was considered as a load, and the metal portions consisting of the pacemaker housing and the lead wire of the electrode were considered as two elements of a receiving antenna. Interference voltages induced through the connector were analyzed by using the finite-difference time-domain method in conjunction with a torso and mobile phone model. The modeling was validated by comparison with previously reported experimental results.**

***Index Terms*—Electromagnetic interference, FDTD analysis, implanted pacemaker, mobile telephone.**

I. Introduction

THERE HAS never been an electromagnetic (EM) field source that may approach so close to an implanted cardiac pacemaker before mobile phones proliferate. This implies a potential for electromagnetic interference (EMI) to the implanted pacemaker. Extensive investigations for the EMI problem of pacemakers have been conducted experimentally or analytically, and recommendations for the health risk management of implanted pacemaker users have been developed in various countries [1]–[5].

The Pacemaker Committee of Japan recently tested more than 200 pacemakers commercially available in Japan using a measuring setup with a homogeneous phantom model [4], [5]. The experimental results showed that the EM fields coupling into the shielded housing of the pacemaker from mobile phones must have caused interference to internal electronic circuits through the connector between the shielded housing and the lead wire of the electrode. As a result, the Pacemaker Committee of Japan concluded that the connector between the pacemaker housing and the lead wire of the electrode plays a major role for the EMI due to mobile phones. This shows that a pacemaker acts as a receiving antenna with respect to the EM fields from a mobile phone. The same idea was also suggested by Ruoss *et al.* [6], in which they pointed out that the electrode has an effect like an antenna.

Based on this finding, a model for predicting interference voltages induced through the connector due to a mobile phone is presented in this paper, in which the internal impedance seen from the connector is considered as a load, and the metal portions consisting of the pacemaker housing and the lead wire of electrode are considered as two elements of a receiving antenna. The finite-difference time-domain (FDTD) method [7] is employed as a tool for analyzing the pacemaker model because of its flexibility in solving complex geometries. The analyzing results for the interference voltages through the connector are used to predict the EMI level, and the predicted results are compared with the previously reported experimental results.

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II. Modeling and Prediction Method

Fig. 1 shows a basic configuration for a pacemaker implanted in a human body and a mobile phone in the vicinity of the body. Fig. 1(a) shows an appearance of the torso and mobile phone model, and Fig. 1(b) depicts cross sections through the pacemaker location at the y–z- and z–x-planes, respectively. Fig. 2(a) shows a diagram of current flowing through the connector. By considering the internal impedance seen from the connector as a load, and the metal portions consisting of the pacemaker housing and the lead wire of the electrode as two elements of a receiving antenna, the resultant equivalent circuit for the pacemaker can be shown in Fig. 2(b).

Here, Z_R is the radiation impedance of the pacemaker, V_o is the open voltage induced between the pacemaker housing and the lead wire due to the EM fields from the mobile phone, Z_I is the internal impedance of the pacemaker seen from the connector, and V_I and I_I are the voltage and current induced through the connector, respectively, that are referred here as the interference voltage and current for the pacemaker, respectively. The prediction for the EMI level is then accomplished through a multistep approach as follows.

Step 1) Determine the radiation impedance Z_R of the pacemaker. This impedance is obtained by simulating the pacemaker as a transmitting antenna, i.e., applying a source voltage at the connector to drive the electrode and lead wire against the shielded housing. The current flowing through the connector is then obtained from the FDTD-computed circumferential magnetic fields according to Ampere's law, and the radiation

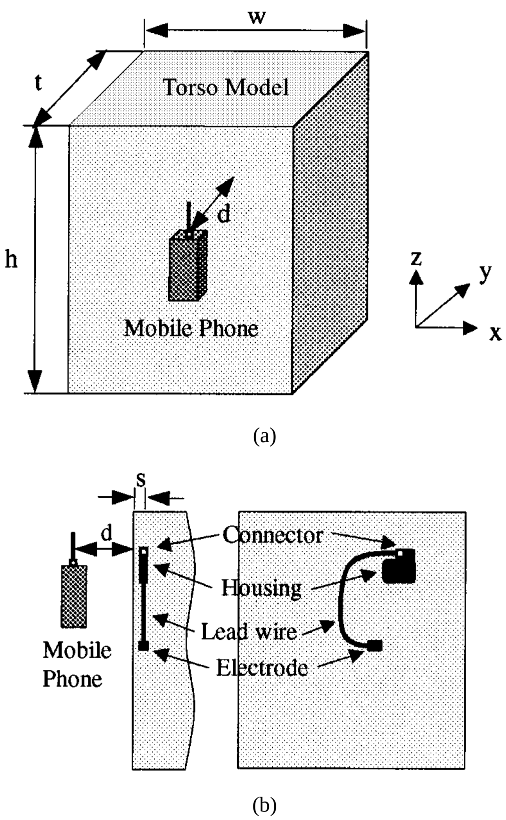

Fig. 1. Mobile phone model and pacemaker model inside human torso. (a) Appearance of the mobile phone and torso models. (b) Cross sections through the pacemaker location at y–z- and z–x-planes.

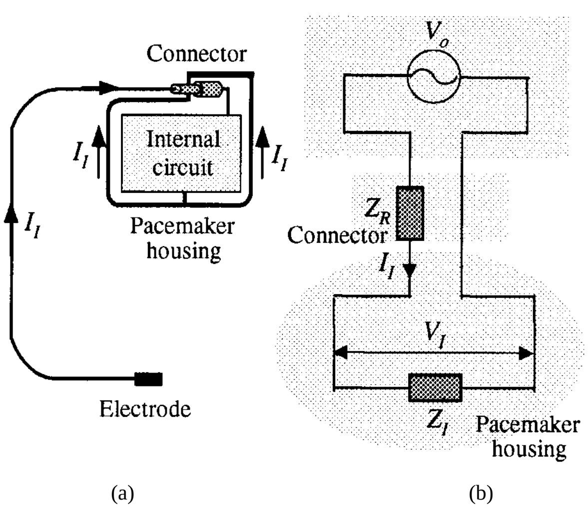

Fig. 2. (a) Diagram of current flowing through the connector. (b) Equivalent circuit for a pacemaker as a receiving antenna.

impedance is determined from the ratio of the source voltage to the current at the connector.

Step 2) Determine the open-voltage V_o at the connector. This voltage is obtained by simulating the pacemaker as a receiving antenna with an open load at the connector. The mobile phone is excited and then the induced voltage between the shielded housing and the lead wire is computed as the open voltage also using the FDTD method, which will be explained later.

Step 3) Calculate the interference voltage V_I through the connector to the input of the internal pacemaker circuit from

$$V_I = \frac{Z_I}{Z_R + Z_I} V_o \tag{1}$$

where Z_I is the internal impedance of pacemaker seen from the connector.

Likewise, if necessary, the interference current I_I can be obtained from

$$I_I = \frac{1}{Z_R + Z_I} V_o \tag{2}$$

to which the pacemaker circuit may be susceptible.

For computing the open-voltage V_o in the Step 2) using the FDTD method, a lumped resistor R is modeled in one FDTD cell. Consider the resistor to be x-directed and let V_L be the voltage at the resistor. The current flowing along it at the $(n - 1/2)$ time step is then

$$I_L^{n-(1/2)} = \frac{V_L^{n-(1/2)}}{R} = \frac{\Delta x}{R} \frac{E_x^{n-1} + E_x^n}{2} \tag{3}$$

where E_x is the electric-field component at the resistor location and Δx is the cell size in the x-direction. From Maxwell's equation, the corresponding time-stepping relation for electric field E and magnetic field H at the resistor is then given by

$$E_x^n = \frac{1 - \dfrac{\Delta t \Delta x}{2R\varepsilon \Delta y \Delta z}}{1 + \dfrac{\Delta t \Delta x}{2R\varepsilon \Delta y \Delta z}} E_x^{n-1} + \frac{\dfrac{\Delta t}{\varepsilon}}{1 + \dfrac{\Delta t \Delta x}{2R\varepsilon \Delta y \Delta z}} \left(\nabla \times H^{n-(1/2)}\right)_x. \tag{4}$$

When $R \to \infty$, the voltage V_L can be considered as the open-voltage V_o.

III. Modeling Validation

The EMI predicting model was checked by using a homogeneous torso model as in the measuring setup employed by the Pacemaker Committee of Japan. The torso model had a dimension of 250 (width) $\times$ 500 (height) $\times$ 70 (thickness) mm and a dielectric property of muscle. A pacemaker model was implanted 15-mm deep into the torso surface. The pacemaker housing had a dimension of 40 $\times$ 30 $\times$ 7.5 mm, and the lead wire of electrode had a diameter of 2.5 mm and a length of about 225 mm. All of the shielded housing, electrode, and lead wire were modeled with perfect conductors. The mobile phone was simplified as a half-wavelength dipole antenna and the frequency was 900 MHz, which is being employed in the Japanese personal digital cellular (PDC) system.

First, the radiation impedance Z_R was computed with the FDTD method by applying a source voltage at the connector location. The FDTD cell size was 2.5 mm and the time step was 4.8 ps. Twelve perfectly matched layers (PMLs) were employed

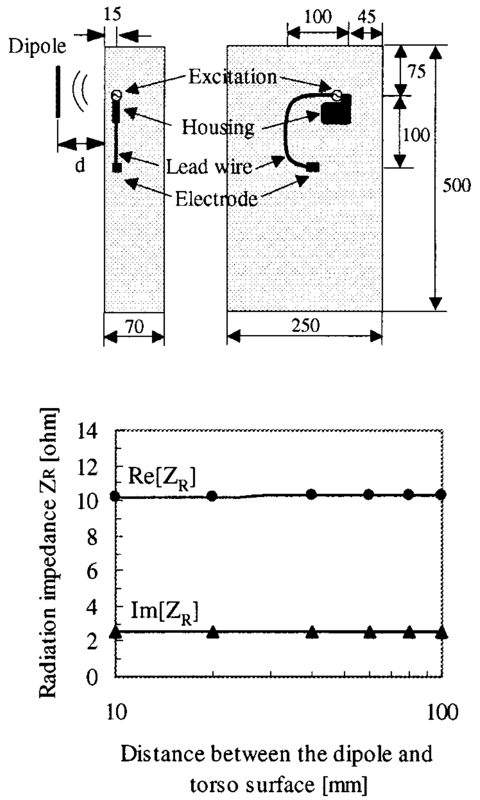

Fig. 3. Radiation impedance Z_R at the connector of pacemaker.

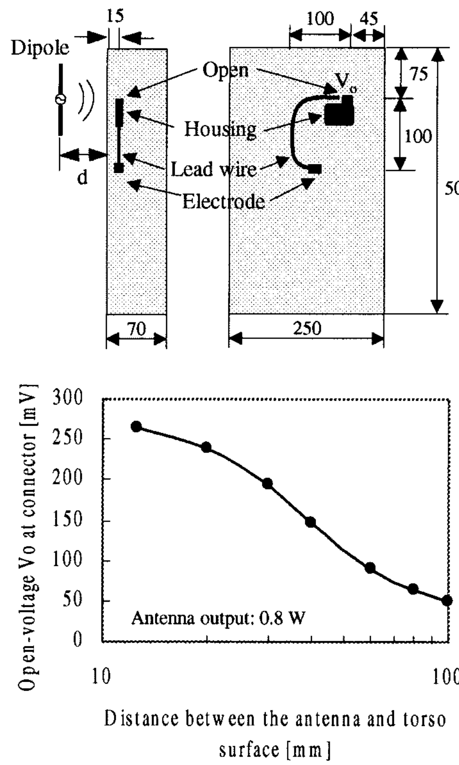

Fig. 4. Open-voltage V_o at the connector of pacemaker for a half-wavelength dipole antenna.

as the absorbing boundary conditions. It should be noted that the half-wavelength dipole antenna was not excited, i.e., it had a source voltage zero in this step. Fig. 3 shows computed Z_R as a function of the distance d between the dipole and torso surface. It was found that Z_R was almost independent of the distance from the dipole antenna. This means that the interference voltage V_I is directly proportional to the open-voltage V_o at the connector according to (1). Moreover, due to the same reason, the interference current I_I is also directly proportional to the open-voltage V_o according to (2). As a result, it is reasonable to use the open-voltage V_o as an index for evaluating the EMI level due to mobile phones.

To obtain V_o, the connector of the pacemaker was replaced by a resistor R and the mobile phone was excited with a source voltage. The resistor value was changed from 100 kΩ to 10 MΩ and found that 1 MΩ is sufficiently large to obtain a stable FDTD-computed voltage value. The FDTD-computed voltage at the resistor R with a value of 1 MΩ was then used as the open-voltage V_o at the connector. Fig. 4 shows the open voltage as a function of the distance d between the dipole and torso surface. The antenna output was 0.8 W.

From these results, we examined the quantitative relationship between the antenna power and the distance that causes EMI to the pacemaker. To determine the interference voltage through the connector from (1), we need to have a prior knowledge about the internal impedance Z_I. When Z_I is sufficiently large compared to Z_R, the interference voltage V_I has a similar level to the open-voltage V_o, which should be applied to the internal circuit through a low-pass filter. Thus, from Fig. 4, we can evaluate that the interference voltage coupled into the internal circuit would have an order of 1.1 mV (for a 40-dB low-pass filter)–11 mV (for a 20-dB low-pass filter) at an antenna distance of 50 mm. Irnich *et al.* reported that the mean value for the sensitivity of actual pacemakers is 1–2 mV [3]. If the interference voltage exceeds the sensing threshold, a malfunction of pacemaker must occur. As can be seen from Fig. 4, a possibility of EMI to the pacemaker indeed exists for a close distance from the body. In fact, one of the authors has reported that 35% of tested pacemakers were interfered by a 900 MHz half-wavelength dipole antenna [5].

Fig. 5 shows a predicted relationship between the antenna power and interference distance. The interference distances was obtained by assuming an open-voltage (V_o) threshold of 120 mV.[1] When the induced open voltage at the connector was larger than the threshold, the interference was considered to occur. Also shown in this figure are measured relationships reported in [4] by one of the authors in which the same torso model and four different pacemakers were used. As can be seen from Fig. 5, the predicted result shows a fair agreement with the measured ones, which verifies the validity of the above-mentioned predicting model.

One prediction required 3.5 h for a 500-MHz Pentium III CPU and approximately 200-MB memory. This means that the computation time and resource for the multistep prediction are at a reasonable level for actual uses.

[1]By comparing Fig. 4 with the experimental relationship between the affected rate of the pacemaker and the distance from the body in [4], we found that the open voltage of 120 mV corresponds to an affected rate of 30%.

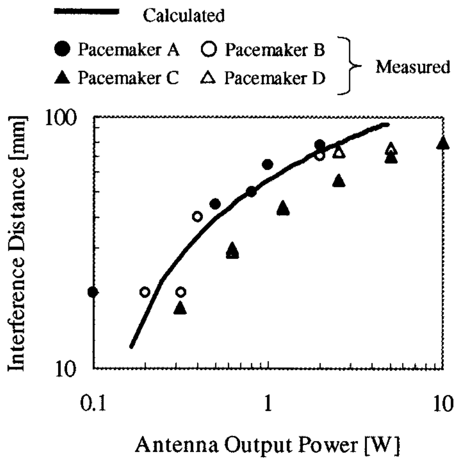

Fig. 5. Interference distance versus antenna output power. The interference distance was defined as the distance where the interference voltage exceeds the threshold value, resulting in a malfunction in the pacemaker. The calculated result was obtained by assuming a threshold open voltage of 120 mV at the connector, which corresponds to an affected rate of 30%. The measured results were cited from [4].

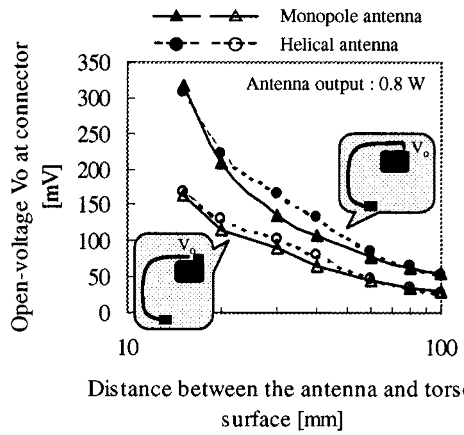

Fig. 6. Open-voltage V_o at the connector of a pacemaker induced by a mobile phone model with a quarter-wave monopole antenna or a helical antenna. The pacemaker model had the same shape and size for the shielded housing, lead wire, and electrode, except for the structure in the vicinity of the connector, i.e., one connector had a horizontally directed structure and the other one had a vertically directed structure.

TABLE I
DIELECTRIC PROPERTIES OF TISSUE AT 900 MHz

Tissue	ε_r	σ [S/m]
skin	41.41	0.87
fat	11.33	0.11
muscle	55.96	0.97

IV. PREDICTION FOR DIFFERENT ANTENNAS AND PACEMAKERS

The multistep EMI prediction is useful to evaluate EMI levels for different antennas and pacemaker structures and, thus, to provide design guidelines from the point-of-view of immunity. A few cases are presented herein for the EMI predictions by means of the open-voltage V_o at the connector of pacemaker.

First, two different antenna structures of mobile phones, i.e., a quarter-wave monopole antenna and a helical antenna both mounted on a rectangular conducting box were considered. The quarter-wave monopole antenna had a length of 82.5 mm and a radius of 2.5 mm. The helical antenna had a length of 16 mm, a pitch of 2 mm, a diameter of 4 mm, and modeled as a stack of dipoles and loops in the FDTD computation according to [9]. Both the monopole and helical antennas were mounted on the center of the top of the conducting box with a dimension of $40 \times 20 \times 120$ mm.

A torso model, which is more similar to the actual size of a human torso, was used in the forthcoming computations. The torso model was a three-layer rectangular one with a dimension of 300 (width) $\times$ 400 (height) $\times$ 160 (thickness) mm, and the three layers were skin (2.5-mm thick), fat (10-mm thick) and muscle, respectively. Their dielectric properties at 900 MHz are shown in Table I [8]. It should be noted that the dielectric properties for muscle in Table I are similar to those for the phantom model in [4]. The pacemaker model, which was implanted 15-mm deep into the skin surface, was the same as that used in the previous section.

Fig. 6 shows predicted open voltages at the connector as a function of the distance between the antenna elements and the torso surface for both the monopole and helical antenna mobile phones. The induced open voltages exhibited some different characteristics for the two antennas. The induced open voltage for the helical antenna had a slower attenuation with the distance than the monopole antenna at a distance smaller than 60 mm, while it had almost the same level as the quarter-wave monopole antenna at a distance larger than 60 mm. Compared with the computed open voltage for a half-wavelength dipole antenna (see Fig. 4), the mobile phone models induced less interference voltages for the pacemaker. For example, for inducing a open voltage of 100 mV, with respect to the distance d between the half-wavelength dipole antenna and the torso surface, the distance d between the mobile phone models and the torso surface was reduced approximately to 50% $\sim$ 60%. The predicted results were identical to the experimental results reported in [4] by one of the authors, in which the interference distance for actual mobile phones was reported to be only 62% of that for a half-wavelength dipole antenna.

Another case was investigated for different structures of the connector of a pacemaker. Being different from the x-directed connector for the above case, the connector was arranged to be z-directed by adjusting the structure in the vicinity of the connector, as shown in Fig. 6. The other parts such as the shielded housing, lead wire, and electrode were kept the same.Fig. 6 also shows predicted open voltages at the connector as a function of the distance for such a connector structure. Due to the same directivity between the antennas and connector, the induced open voltages were larger than that through the x-directed connector. This observation suggests that the connector shape and configuration is a key element in the pacemaker design from the point-of-view of immunity.

V. CONCLUSIONS

A model has been presented for predicting the EMI levels of implanted pacemakers due to mobile phones. In the model, the internal impedance looked from the connector has been considered as a load, and the metal portions consisting of the pacemaker housing and the lead wire of the electrode have been considered as two elements of a receiving antenna. The EMI levels have been predicted by a multistep approach. Predicted results have shown a fair agreement with measured ones for actual pacemakers. Furthermore, some simple examples have been shown for illustrating the usefulness of the multistep prediction. These examples have also demonstrated that the connector configuration of pacemakers is susceptible to the EMI from mobile phones and the interference voltages through the connector is antenna dependent. With the aid of the predicting model, design guidelines for pacemaker structure and immunity capacity can be developed.

Although the open voltage at the connector has been proven to be an index for evaluating the EMI levels of pacemakers, there is a factor for converting it to the actual interference voltage induced on pacemaker circuits. Derivation of this factor requires measurements for actual pacemaker devices, which would be a subject of future discussion.

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