DETERMINATION OF THRESHOLD VALUES OF ELECTROMAGNETIC NEAR-FIELDS FOR PATIENTS WITH IMPLANTED PACEMAKERS IN THE FREQUENCY RANGE 30KHZ - 50MHZ

X. Xu and V. Hansen
Bergische Universität Gesamthochschule Wuppertal, D-42097 Wuppertal, Germany

Abstract

In order to protect persons with implanted pacemakers, threshold values of electromagnetic fields should be prescribed. In the German standard DIN VDE 0848 threshold values in the frequency range 30 kHz - 50 MHz are only given for far-fields. However, near-fields have usually higher densities and their behavior is much more complicated than that of far-fields. Therefore, it is significant to determine threshold values of near-fields. In this work, we follow the following procedure: 1. The near-field is characterized by using a Taylor series with a few terms. 2. The induced field in the human body is calculated for each single Taylor term. 3. The coupling mechanism of each single Taylor term is investigated for a number of different pacemaker models at different locations. 4. Threshold values of the near-field are determined regarding the maximum allowed disturbing voltage at the entrance of the implanted pacemaker. This procedure is also applied to far-field problems and exhibits a very good agreement with the known threshold values.

1. Introduction

In the field of electromagnetic compatibility and protection of persons, it is desirable that the danger probability for people in a certain area can be obtained directly from local measurements of electromagnetic fields [1]. It is possible to define threshold values of electromagnetic fields for persons with pacemakers if the relation between the field at absence of the human body and the disturbing voltage induced by this field at the entrance of the pacemaker is known. The maximum allowed disturbing voltage is prescribed in the German Standard DIN VDE 0848. In order to achieve this goal, one has to characterize electromagnetic fields with the help of a few parameters. Attempts have been made with conventional methods e.g. the multipole method and the plane wave expansion. But those methods do not lead to a substantial reduction of the number of parameters with which near-fields can be described.

In Section 2, a Taylor series is introduced to characterize electromagnetic fields in a region, whose size is much smaller than the wavelength and the distance between this region and the sources. It is also shown, how the Taylor coefficients can be determined from the measured field densities in this region considering the constraints due to Maxwell's equations. The total field is then a sum of the products of the dimensionless Taylor coefficients and the fields of single Taylor terms. In Section 3, the induced field in the human body is calculated for each single term. Then, the disturbing voltage at the entrance of the pacemaker is investigated in Section 4 for a number of different pacemaker models. Considering that the total disturbing voltage should not exceed the maximum allowed disturbing voltage, threshold values can be given in concrete cases.

2. A General Taylor Series and Constraints

A general expression of the electric and magnetic field strength in a source-free area can be written in the following way:

$$\vec{E} = \sum_{l+m+n=0}^{\infty} \vec{E}_{lmn} x^l y^m z^n \, , \quad \vec{H} = \sum_{l+m+n=0}^{\infty} \vec{H}_{lmn} x^l y^m z^n \, . \tag{1}$$

We concentrate our attention to the magnetic field density because of the similarity of the two fields. By substituting the equation into the wave equation and the equation $\nabla \cdot \vec{H} = 0$, one obtains

$$(l+2)(l+1)\vec{H}_{l+2mn} + (m+2)(m+1)\vec{H}_{lm+2n} + (n+2)(n+1)\vec{H}_{lmn+2} + k^2\vec{H}_{lmn} = 0 \, , \tag{2}$$

$$\vec{e}_x(l+1)\vec{H}_{l+1mn} + \vec{e}_y(m+1)\vec{H}_{lm+1n} + \vec{e}_z(n+1)\vec{H}_{lmn+1} = 0 \, , \tag{3}$$

where k is the wave number. In a small area, one needs only a few Taylor terms to describe the magnetic field:

$$\vec{H}_t(x,y,z) = \vec{H}_1 + x\vec{H}_2 + y\vec{H}_3 + z\vec{H}_4 + x^2\vec{H}_5 + y^2\vec{H}_6 + z^2\vec{H}_7 + xy\vec{H}_8 + xz\vec{H}_9 + yz\vec{H}_{10} \, . \tag{4}$$

Equations (2) und (3) can be represented by 7 constraints,with which the coefficients $\vec{H}_1 \ldots \vec{H}_{10}$ are determined from the measured field data. In order to compensate for the errors in the measurements and to maintain the physical properties of the field, one must consider the 7 conditions determining the coefficients. For this purpose, the least squares method of Gauss and the method of Lagrange's multipliers are employed [2]. Denoting the measured fields and the fields described by the Taylor series with the index m and t, respectively, one has only to find the coefficients which minimize the expression

$$S = \sum \left[(H_{xm} - H_{xt})^2 + (H_{ym} - H_{yt})^2 + (H_{zm} - H_{zt})^2 \right] \tag{5}$$

under the constraints, where the sum is over all points at which the field is measured. It follows a linear algebraic equation system from which the coefficients can be determined with a sufficient number of measured data.

As an example we show a log-periodic antenna with 10 elements located in the xz-plane (Fig 1). Between two adjacent elements there are relations $h_{n+1}/h_n = d_{n+1}/d_n = 0.83$. The first element has a length of 5 m and a radius of 5 mm. The elements are crossways connected by a double transmitting line of a wave impedance 50 Ω and fed at the middle of the shortest element with $1V$ at 30 MHz. The near field is computed by using the method of moments. In a cube of $(2.4\ m)^3$ with its center at the point (0.2 m, 6.2 m, 0.2 m), the Taylor coefficients are calculated by the method described above. The field distribution reconstructed with the Taylor coefficients by using Equation (4) only differs a little from that calculated using the method of moments. The error is less than 1%.

3. Calculation of the electromagnetic field in the human body

The electromagnetic field in the human body induced by the single terms should be calculated in this section. As the single terms do not satisfy all Maxwell equations, we replace the single terms by single Huygens' sources [3], whose fields satisfy Maxwell's equations. With the help of the Huygens' sources, we can construct fields in the volume V_A which are very similar to the original Taylor terms. For example, if one places an electric current sheet $\vec{J}_A^{2y} = \vec{n} \times \vec{e}_y\, x\, [A/m^2]$ immediately inside a cuboid, whose outer space is filled with ideal magnetic material, one obtains a magnetic field in the cuboid which differs hardly from $\vec{e}_y\, x\, [A/m^2]$.

The numerical calculation of the field in the human body is performed by using the Finite Integration Technique [4]. Fig. 2 shows the body model and the pattern of the magnetic field in the volume with the human body at 30 MHz in the plane $y = 0\ m$ for the electric current sheet $\vec{J}_A^{2y}$. One can see that the magnetic field in the volume is almost linear in x like that in the volume without the human body. Similarly, the electromagnetic fields in the human body for other terms are calculated [5].

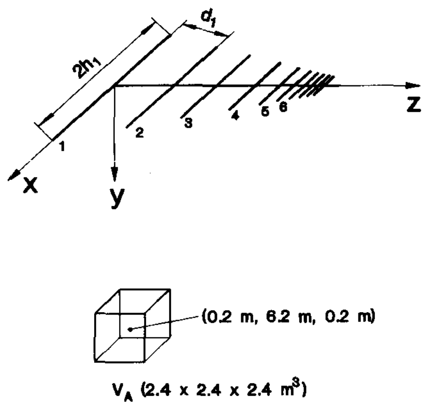
4. Coupling in the pacemaker and threshold values of electromagnetic near-fields

With the knowledge of the field in the human body, the disturbing voltage for all single terms can be calculated by using the method of moments. The case and the electrode of the pacemaker are modeled by a grid, in which the influence of the entrance impedance and isolation of the electrode can be investigated. For a set of Taylor coefficients, it is then easy to obtain the total disturbing voltages by summing the voltage for all single terms. In order to determine threshold values of electromagnetic fields, it is necessary to consider different positions of the pacemaker and electrode because of different implanting techniques employed. Therefore, the disturbing voltage was calculated for 36 different positions and configurations of the pacemaker and the electrode. The maximum value of the total disturbing voltage for the magnetic field $U_{St\,\max}^H$ and the electric field $U_{St\,\max}^E$ can be written as

$$U_{St\,\max}^H = \sum_{n=1}^{10} \sum_{\alpha}^{x,y,z} [\left|\frac{H_{n\alpha}}{[H_{n\alpha}]}\right| |U_{n\alpha}^H(k_{\max})|], \quad U_{St\,\max}^E = \sum_{n=1}^{10} \sum_{\alpha}^{x,y,z} [\left|\frac{E_{n\alpha}}{[E_{n\alpha}]}\right| |U_{n\alpha}^E(k_{\max})|], \tag{6}$$

where $H_{n\alpha}/[H_{n\alpha}]$ and $E_{n\alpha}/[E_{n\alpha}]$ are the dimensionless coefficients and $U_{n\alpha}^H(k_{\max})$ and $U_{n\alpha}^E(k_{\max})$ the disturbing voltages for the single terms in the worst case. We obtain an estimate of the disturbing voltage independent of the position of the pacemaker system. The safety of persons with pacemakers in antenna fields is guaranteed if

$$U_{St\,\max}^H \leq U_{SS}/2, \; U_{St\,\max}^E \leq U_{SS}/2, \tag{7}$$



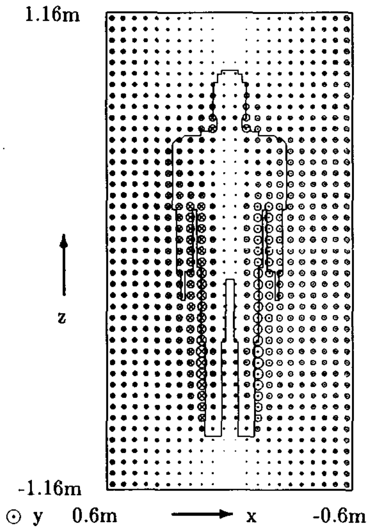


Fig. 1: Geometry of the logarithmic-periodic antenna

Fig. 2: Real part of the magnetic field $\vec{H}_{Jm}^{(x,y)}$ in the volume with the human body, generated by Huygens' current sheet $\vec{J}_A^{2y}$ (max. 1,46 A/m)

where $U_{SS}/2$ is the maximum magnitude of the disturbing voltage defined in Section 4.2.2.1.1 of Part 2 of the German standard DIN/VDE 0848.

At 30 MHz the maximum top magnitude is 0.145 V. With the coefficients for the field in the volume V_A near the logarithmic-periodic antenna calculated in Section 2, we conclude that the feeding voltage of the logarithmic-periodic antenna should not exceed 244 V.

The concept was also applied to far-field problems. The comparison of our results with those in DIN VDE 0848 shows a very good agreement in the frequency range up to 10 MHz (see the following Table). At 3 MHz, for instance, we have a threshold value of 14.6 V/m, whereas that in DIN VDE 0848 is 16.1 V/m.

Threshold values	$\hat{E}$/0.3MHz	$\hat{E}$/3MHz	$\hat{E}$/30MHz	$\hat{H}$/0.3MHz	$\hat{H}$/3MHz	$\hat{H}$/30MHz
DIN VDE 0848	48.4 V/m	16.1 V/m	4.1 V/m	0.128 A/m	0.043 A/m	0.011 A/m
Taylor Series	38.4 V/m	14.6 V/m	7.7 V/m	0.114 A/m	0.036 A/m	0.018 A/m

Aknowledgement

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