Electric Fields Induced in Cells in the Bodies of Amateur Radio Operators by Their Transmitting Antennas

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***Abstract*—In this paper, an analytical study is made to determine the electric field induced in cells in the bodies of amateur radio operators by radiation from their respective transmitting antennas. Three types of antennas are considered and the electric field from each in the transmitting room of the operator is calculated. The electric field induced in the bodies of the operators is obtained with a cylindrical approximation of the body. The electric field induced in a cell in the central cross section of the body at $f = 60$ MHz when the antenna radiates 1 kW is found to be as high as 50 V/m when the cell is near the surface. Due to skin effect, the field is much smaller in the interior of the body.**

***Index Terms*—Biological cells, biological effects of electromagnetic radiation, electric fields, electromagnetic radiation effects, HF radio propagation, HF transmitters, transmitting antennas.**

I. Introduction

AMATEUR radio operators are exposed to electric fields during periods of transmission that induce significant electric currents and fields in their bodies. These penetrate cells in the tissues. In recent years, many different pathways have been explored as potential candidates for cancer initiation and promotion. A recently described possibility is faulty centrosome replication in the cell [1], [2]. Centrosomes are small bodies near the nucleus of a cell. The question immediately arises: Can an electric field of sufficient intensity and duration when induced in the cell have biomedical consequences? For example, when induced between the cell membrane and nuclear envelope, can it produce or stimulate faulty action of the centrosomes? How intense is the electric field induced in the cells of an amateur radio operator? A quantitatively meaningful answer involves the following sequence of steps.

- Step 1) A study of various types of transmitting antennas used by radio amateurs.
- Step 2) The calculation of the electric field generated by typical transmitting antennas in the interior of houses where the operator sits.
- Step 3) The calculation of the electric field induced in the body of an operator. This involves significant skin effect at the frequencies involved.
- Step 4) The calculation of the electric field induced in the cells.

A beginning to the outlined analysis has been made in a recent paper [3] to which frequent reference will be made.

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Before beginning this study, it is appropriate to review briefly earlier work on related topics including dosimetry. Among the numerous references are two books, one by Gandhi [4] and the other by Silver [5], which provide a broad background of work over a wide range of frequencies. They also include long lists of references. Supplementing these is a Federal Communications Commission report [6], which establishes general guidelines and information concerning recommended limits of exposure at all frequencies. Schmid *et al.* [7] describe an automated E-field scanning method, Kuster [8] develops the multiple multipole method for simulating electromagnetic problems involving biological bodies, Johnson and Guy [9] discuss electromagnetic-wave effects on biological materials, Karimullah *et al.* [10] analyze coupling between wire antennas and a biological body, and finally, Chuang [11] describes the computation of the effect of fat layers on microwave near-field radiation to the abdomen of full-scale human models. A broad variety of studies relating to biological effects of electromagnetic fields is contained in a special issue of PROC. IEEE [12]. Of interest in this study are papers on population exposure to VHF and UHF broadcast radiation, occupational exposure to RF electromagnetic fields, electromagnetic absorbed doses in man and animals, electromagnetic dosimetry for models of humans and animals, microwave biological effects, and RF field interactions with biological systems. None of these studies treats specifically the 50–60-MHz amateur radio band, which is of importance because it coincides with the resonant frequency of the human body and the largest electric field induced in that body. At any of the many other amateur radio bands, the electric field in the human body is greatly reduced and, with it, any possible effects on cellular processes.

II. Transmitting Antennas and the Electric Field They Generate

Amateur radio transmitting antennas are of many types. Large fixed installations include broadside, end-fire, and collinear arrays. Since such arrays are usually quite far from the operator's residence, they are probably not among those that maintain large fields in the houses. Smaller antennas that have been selected from actual ones known to and examined by the author include omnidirectional vertical dipoles, such dipoles with rotatable parasitic reflector and single director to provide directivity, and rotatable horizontal Yagi–Uda arrays. Calculations will be made for these three types.

There are many amateur RF bands. However, since the 50–60-MHz band includes the resonant frequency $f = 53$ MHz of the human body and, hence, involves the largest induced current, attention will be directed specifically to this band.

A. Vertical Dipole Antenna

A complete analysis has been made [3] of the electric field generated by a vertical dipole with the half-length $L \sim \lambda/4$ or electrical half-length $k_2L \sim \pi/2$, where $k_2 = \omega/c$ is the wave number of air. The vertical component of the electric field for the antenna at a horizontal distance ρ is

$$E_{2z}(\rho, z) = -\frac{j\omega\mu_0 I_z(0)}{4\pi k_2}\left(\frac{e^{-jk_2r_{1L}}}{r_{1L}} + \frac{e^{-jk_2r_{2L}}}{r_{2L}}\right) \quad (1)$$

$$r_{1L} = \left[(L-z)^2 + \rho^2\right]^{1/2}$$
$$r_{2L} = \left[(L+z)^2 + \rho^2\right]^{1/2}. \quad (2)$$

For the antenna involved here, $\rho = 10$ m is the distance from the antenna to the operator when transmitting. For a transmitted power of $P = 1$ kW, the current $I_z(0)$ is $I_z(0) = (P/R)^{1/2} = (10^3/73)^{1/2} = 3.7$ A. Here, $R \sim 73\ \Omega$ is the radiation resistance of the center-driven antenna. With the center of the antenna at $z = 5$ m above the surface of the earth, the point of observation at the same height, and $\rho = 10$ m

$$E_{2z}(10, 5) = -2.27 - j21.89 = -j22.0e^{-j12.67} \text{ V/m.} \quad (3)$$

If it is assumed that the walls of the house are made of dielectric materials like wood, brick, and plaster and, therefore, provide no shielding, as shown in [13], (3) gives the direct field in the house at a height of $z = 5$ m above the earth. When combined with the associated image field due to the proximity to the earth, the total field in the house is [3]

$$E_{2z}(10, 5) = 25.0e^{-j1.4} \text{ V/m.} \quad (4)$$

This is the vertical electric field acting on a person in the house at a distance $\rho = 10$ m from the radiating antenna when this emits 1 kW of power.

B. Vertical Dipole with Reflector and Single Director

The directional effect of a reflector and director (shown in Fig. 1) on the field pattern depends on the lengths and spacing of these elements. The conditions for maximum front-to-back ratio, maximum directivity, or minimum sidelobes differ significantly. In general, the length of the driven element is $2h_2 = 0.5\lambda$, the length of the reflector is $2h_1 = 0.51\lambda$, and the length of the director is between $2h_3 = 0.44\lambda$ and $2h_3 = 0.46\lambda$. The reflector is at $b_{12} = 0.25\lambda$ from the driven element, and the director is at $b_{23} = 0.1\lambda$ to $b_{23} = 0.25\lambda$ from the driven element. It is the length and spacing of the director that are primarily useful in determining the type of field pattern. Graphs and tables showing a wide range of possibilities are in [14]. The effect of the reflector and director is to increase the forward field by a factor of two or more and decrease the backward field to a small fraction of the forward field. This means that when the antenna directs its maximum field toward the operator's house,

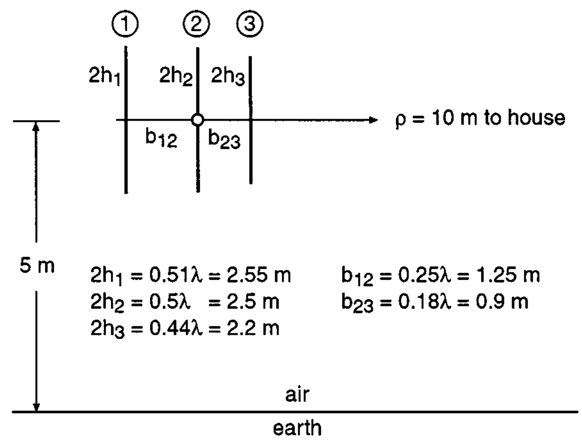

Fig. 1. Schematic diagram of vertical three-element Yagi–Uda array. Elements 1 and 3 are rotatable together around element 2. Operating frequency $f = 60$ MHz, $\lambda = 5$ m.

the vertical electric field acting on a person's body in the house, as given by (4), becomes

$$\left|E_{2z}(10, 5)\right| \geq 50 \text{ V/m.} \quad (5)$$

C. Horizontal Yagi–Uda Array

A representative Yagi–Uda array consists of a horizontal reflector, a driven element, and several directors attached to a rotatable mast above the roof of the operator's house. A good approximation of the near field of such an array in the house below the array is the near field of a horizontal half-wave dipole. In the actual array, the current is divided among the several elements, which are displaced from the driven element by successive fractions of a wavelength. The field of each is like that of the dipole, but displaced a short distance. The field of all the elements is well approximated by that of the driven element radiating all the power. If the roof of the house is made of wood and asphalt, it has no effect on the interior below it [13]. Consider the vertical electric field of the dipole shown in Fig. 2 at a point on the second floor of the house where the operator's transmitting room is located. The second floor is 7.5 m above the earth and 7.5 m below the horizontal antenna above the roof. The radial electric field of the dipole is the vertical electric field in the house. It is given by [15, p. 600, formula A-VI-33], viz.

$$E_\rho^d = \frac{j\omega\mu_0 I(0)}{4\pi k_0 \rho}\left(\frac{z-h}{R_1}e^{-jk_2R_1} + \frac{z+h}{R_2}e^{-jk_2R_2}\right). \quad (6)$$

At $f = 60$ MHz, $k_0 = 0.4\pi$ m^{-1}. With $z = 10$ m, $h = 1.25$ m and $\rho = 7.5$ m, $R_1 = [(z-h)^2 + \rho^2]^{1/2} = (8.75^2 + 7.5^2)^{1/2} = 11.52$ m and $R_2 = [(z+h)^2 + \rho^2]^{1/2} = (11.25^2 + 7.5^2)^{1/2} = 13.52$ m. When the dipole radiates 1 kW, i.e., $I^2R = 10^3$ W, the current $I(0)$ is $I = (10^3/73)^{1/2} = 3.7$ A. Also

$$e^{-jk_2R_1} = \cos k_2R_1 - j\sin k_2R_1 = -0.333 - j0.943 \quad (7)$$
$$e^{-jk_2R_2} = \cos k_2R_2 - j\sin k_2R_2 = -0.285 + j0.958. \quad (8)$$

With these values, the direct field given in (6) is

$$E_\rho^d = -0.12 - j7.252 = -j7.253e^{-j12.58} \text{ V/m.} \quad (9)$$

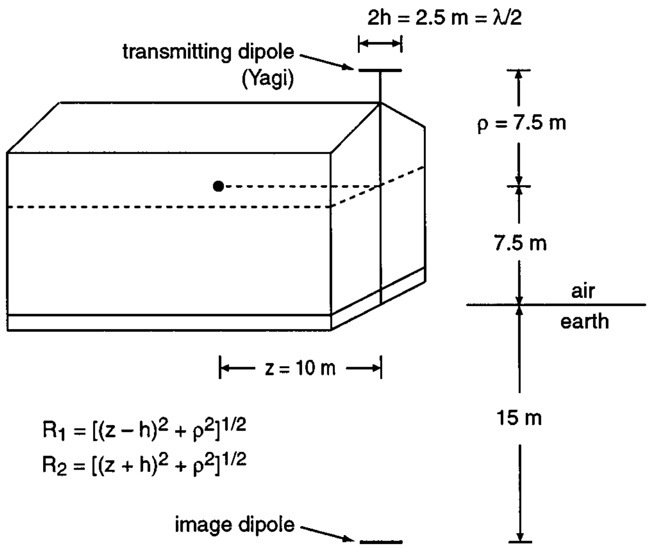

Fig. 2. Operator at • on second floor of two-story house with horizontal Yagi–Uda array or dipole above the roof.

The reflected or image field is

$$E_\rho^i = -\frac{j\omega\mu_0 I(0)}{4\pi k_0 \rho_i}\left(\frac{z-h}{R_1^i}e^{-jk_2R_1^i} + \frac{z+h}{R_2^i}e^{-jk_2R_2^i}\right) \tag{10}$$

where $\rho_i = 22.5$ m and all other quantities are unchanged. It follows that $R_1^i = (8.75^2 + 22.5^2)^{1/2} = 24.14$ m, $R_2^i = (11.25^2 + 22.5^2)^{1/2} = 25.15$ m, $\cos k_2R_1^i - j\sin k_2R_1^i = 0.47 + j0.882$, $\cos k_2R_2^i - j\sin k_2R_2^i = 0.982 - j0.187$, and

$$\frac{z-h}{R_1^i}e^{-jk_2R_1^i} + \frac{z+h}{R_2^i}e^{-jk_2R_2^i} = 0.609 + j0.236. \tag{11}$$

Hence,

$$E_\rho^i = 1.16 - j3.0 \text{ V/m} \tag{12}$$

and

$$\begin{aligned} E_\rho^d + E_\rho^i &= 1.04 - j10.25 \text{ V/m} \\ |E_\rho^d + E_\rho^i| &= 10.30 \text{ V/m}. \end{aligned} \tag{13}$$

This is the vertical electric field to which an operator is exposed when transmitting in a direction for which the dipole is in the same plane as his body. When the dipole is rotated 90° for transmission along the length of the house, the vertical field acting on the operator is zero. The complete field can be expressed as follows:

$$|E_\rho| = 10.30\cos\phi \text{ V/m} \tag{14}$$

where $\phi = 0$ when the dipole is parallel to the ridgeboard of the house. This field is substantially smaller than that of a vertical dipole with a reflector and director. This is because the electric field has only a small component parallel to the length of the body instead of its maximum value.

III. Electric Field Induced in the Human Body

An accurate calculation of the current density $\mathbf{J}_1$ and the electric field $\mathbf{E}_1$ in the human body when exposed to an incident electric field E_{2z}^{inc} is not possible at frequencies as high as 50–60 MHz. This is a consequence of the shape of the body and skin effect in its interior. As discussed in [3], an approximation can be made by representing the body by a cylinder with the same conductivity $\sigma_1 = 0.5$ S/m and relative permittivity $\epsilon_{1r} = 60$ as those of the saline fluid that permeates the body. For a cylinder with the length $2h = 1.75$ m and radius $a = 0.14$ m, the current density and electric field at the center $\rho = 0$ of the midsection of the cylinder are

$$|J_{1z}(0)| = 0.1115|E_{2z}^{\text{inc}}| \tag{15}$$

$$\begin{aligned} |E_{1z}(0)| &= |J_{1z}(0)/(\sigma_1 - j\omega\epsilon_0\epsilon_{1r})| \\ &= |J_{1z}(0)|/0.54 = 0.206|E_{2z}^{\text{inc}}|. \end{aligned} \tag{16}$$

Near the surface $\rho \sim a$

$$|J_{1z}(a)| = 0.2886|E_{2z}^{\text{inc}}| \tag{17}$$

$$|E_{1z}(a)| = |J_{1z}(a)|/0.54 = 0.534|E_{2z}^{\text{inc}}|. \tag{18}$$

With the vertical three-element Yagi–Uda array, $E_{2z}^{\text{inc}} \sim 50$ V/m so that $|E_{1z}(a)| \sim 26.7$ V/m. For the horizontal Yagi–Uda array on the roof, $E_{2z}^{\text{inc}} \sim 10.30$ V/m so that $|E_{1z}(a)| = 5.50$ V/m. It can be concluded that cells near the surface of the body are exposed to electric fields of the order of $|E_{1z}(a)| \sim 5$ to 25 V/m. In the interior of the body, this range is reduced to $|E_{1z}(0)| \sim 2$ to 10 V/m.

IV. Electric Field Induced in Cells

The final step in this paper is the determination of the electric field induced in the interior of cells including the nucleus. At frequencies as high as 60 MHz, the cell membrane and nuclear envelope have the properties of dielectrics and provide no shielding. This has been known since the publication of the extensive work by Foster and Schwan [16]. Accordingly, the electric field in the interior of a cell and the interior of the nucleus is the same as the field in the body outside the cell.

V. Conclusion

A systematic analysis has been made to determine the electric field induced in cells in the bodies of amateur radio operators when they are exposed to the electromagnetic field of their own transmitting antennas at 50–60 MHz. This involved the study of three types of antennas and the accurate calculation of the electric field maintained by them in the transmitting rooms of houses occupied by the radio amateurs. The next step was the calculation of the electric field induced in the human body at $f = 60$ MHz including skin effect. Finally, the field induced in cells was determined. It is hoped that the values of the electric field up to 50 V/m induced in cells near the surface of the body may assist biomedical scientists in determining its effect on cellular processes. Although no direct correlation is possible, the fact that statistical evidence found by Milham [17] indicates an increase in malignancies in some amateur radio operators over that of the general population should not be ignored.

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