SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 1, No. 2, June 2004, 153 - 166

Interaction Between LF Electric Fields and Biological Bodies

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Abstract: In this paper the Equivalent electrodes method is used for electric field calculation in the proximity of the various biological subjects exposed to an electric field in the LF range. Several results of the electric field intensity on the body surface and numerous graphical results for equipotential and equienergetic curves are presented.

Keywords: Biological bodies, Electric field, Equivalent electrodes method.

1 Introduction

The interaction of low frequency (0 Hz - 100 Hz) electromagnetic fields (LF) with the humans and other life forms has become an increasingly important subject since potential health hazards due to the electromagnetic fields emitted by extremely high-voltage power lines and LF antenna systems became a public concern. This subject has been extensively investigated experimentally or empirically by many workers [2 - 5]. A number of projects using oversimplified body geometries or inaccurate methods, and the practical values of their results are questionable.

The Equivalent electrodes method [1], which has been developed at the Faculty of Electronic Engineering in Niš, proved as a very useful method for determining the distribution of the electric field in the proximity of the various biological subjects exposed to an electric field in the LF range. The electric field strength to which a subject exposed is conventionally specified as the unperturbed field that is present before the subject is introduced. Published theoretical estimates indicate that the actual fields to which a subjects is exposed (the fields at the exterior surface and in the proximity of various biological subjects) are different from the unperturbed field.

We will treat the case of biological subjects standing on and in electrical contact with ground plane and exposed to an unperturbed electric field, which is uniform and vertical, because the unperturbed ground level fields produced by high-voltage transmission lines are approximately vertical and uniform. Humans and other biological bodies can be regarded as conductors, so the induced charges are distributed on their surface. Using Dirichlet boundary conditions (subjects have zero potential), it is possible to form integral equations for surface charge density distributions as unknowns. In general case, these equations can not be solved exactly, so approximate numerical method based on

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Equivalent electrodes method will be used for their solution. As a result of the calculation the values for the electric field enhancement factor are obtained. The values for potential and electric field strenghts in the proximity of the various biological subjects are also obtained. Maps of isopotential lines, as well as of equienergetic curves, defining the geometric positions of the points of constant intensity of the electric strength, or of constant energy densities, can also be obtained.

2 Theoretical Approach

The aim of this paper is to determine the distribution of the electric field in the proximity of the various biological subjects exposed to an electric field in the LF range. Our approach is based on an Equivalent electrodes method.

2.1 Equivalent electrodes method

Equivalent electrodes method (EEM) [1] is new numerical method, suggested by professor dr. Dragutin Veličković, and it is used for solving the problems for non dynamic electromagnetic fields and other potential fields of theoretical physics. The basic idea of the proposed theory is: an arbitrary shaped electrode can be replaced by finite system of equivalent electrodes (EE). Thus it is possible to reduce a large number of complicated problems to simple equivalent systems. Depending on the problem geometry, the flat or oval strips (for plan-parallel field) and spherical bodies (for three-dimensional fields), or toroidal electrodes (for systems with axial symmetry) can be commonly used. In contrast to the charge simulation method [8], where the fictitious sources are placed inside the electrodes volume, EE are located on the body surface. The radius of the EE is equal to the equivalent radius of electrode part which is substituted. The potential and charge of the EE and of the real electrode part are also equal. Using Dirichlet boundary conditions, it is possible to form a system of linear equations with charge densities of EE as unknowns. By solving this system, the unknown charge densities of the EE can be determined. The necessary calculations can be based on the standard procedures. In the case when the system has several electrodes, or when the multilayer medium exist, it is convenient to use Green's functions for some electrode or for stratified medium, and after the remaining electrodes to substitute by EE. In the formal mathematical presentations, the proposed EEM is similar to the method of moment [9], but a very important difference exist in physical fundamental and in process of matrix establishment. It is very significant to notice that in the application of EEM no integration is necessary. In the moment method solutions the numerical integration is always present, which produces some problems in the numerical solving of nonelementary integrals having singular subintegral functions.

2.2 Mathematical model

Biological subjects are composed of several parallelepipeds representing various part of the body. The parallelepipeds are replaced by small spherical equivalent electrodes (Fig. 1).

Using method of images, the influence of the base to the human body can be considered and the body potential φ can be presented in the form:

$$\varphi = -E_0 z + \frac{1}{4\pi\varepsilon_0}\sum_{1}^{N} q_n\left(\frac{1}{|\boldsymbol{r}-\boldsymbol{r}_n|} - \frac{1}{|\boldsymbol{r}-\boldsymbol{r}'_n|}\right). \qquad (1)$$

where:

E_0 is intensity of unperturbed field;

N is the total number of spherical equivalent electrodes (EE);

$q_n, n = 1,2.....,N$ is the unknown charge of the n-th EE;

$\boldsymbol{r}$ is radius vector of the field point;

$\boldsymbol{r}_n$ and $\boldsymbol{r}'_n$ are radius vectors of the EE middle point and middle point of the EE image.

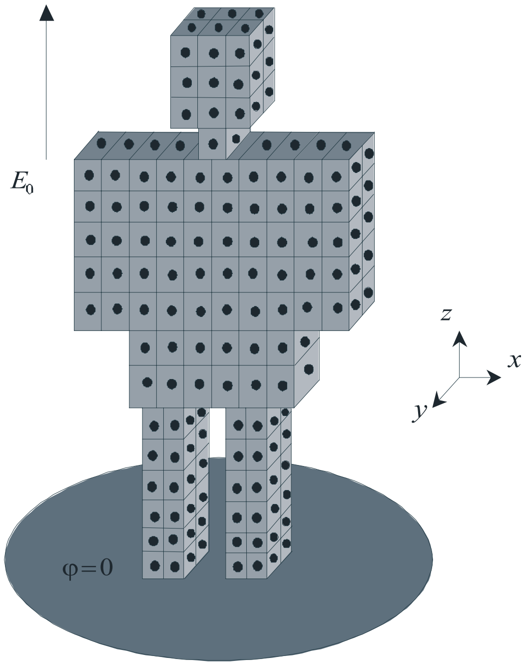

Fig. 1 - *Grounded human body in LF electric field.*

Using boundary condition that the body potential is equal to zero, the following system of N linear equations is formed,

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1N} \\ a_{21} & a_{22} & \cdots & a_{2N} \\ \vdots & \vdots & \vdots & \vdots \\ a_{N1} & a_{N2} & \cdots & a_{NN} \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ \vdots \\ q_N \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_N \end{bmatrix}, \qquad (2)$$

where

$$a_{mn} = h\left(\frac{1}{\sqrt{\left|\boldsymbol{r} - \boldsymbol{r}_n\right|^2 + a_{em}^2 \delta_{mn}}} - \frac{1}{\sqrt{\left|\boldsymbol{r} - \boldsymbol{r}_n'\right|^2 + (2z_m)^2 \delta_{mn}}} \right)$$

and

$$b_m = \frac{z_m}{h}. \tag{3}$$

a_{em} is equivalent radius of thin plate elements with rectangular form and δ_{mn} is Kronecker's symbol.

After solving this linear equation system the magnitudes of the unknown charges of EE will be determined.

Assuming that the induced electric field is totally perpendicular to the body surface, the electric field strength at the body surface is simply obtained form

$$E_n = \frac{q_n}{S_n \varepsilon_0}, \tag{4}$$

where S_n is the surface of the n-th EE and ε_0 is the air permittivity.

The electric field enhancement factor is defined as the ratio of the electric field strength on the surface to the impressed electric field

$$E_n / E_0 = \frac{q_n}{\varepsilon_0 S_n E_0}. \tag{5}$$

3 Numerical Results

3.1 The electric field enhancement factor

We have investigated a model of a pig, a baboon and various models of the human body.

In the numerical calculation, the body surface of pig was partitioned into 448 subareas leading to 224 unknowns when half body symmetry was applied. The results presented in Fig. 2 show the electric field enhancement factor at the various points on the surface of a pig varying from 0.004 on the legs to 4.47 on the top of the pig's back.

The baboon body surface was partitioned into 484 subareas and also half body symmetry was applied. The electric field enhancement factors are presented in Fig. 3. From the figure is evident that the values of the enhancement factor at the various points on the surface of a baboon vary from 0.11 on the legs to 12.65 on the top of the baboon's head.

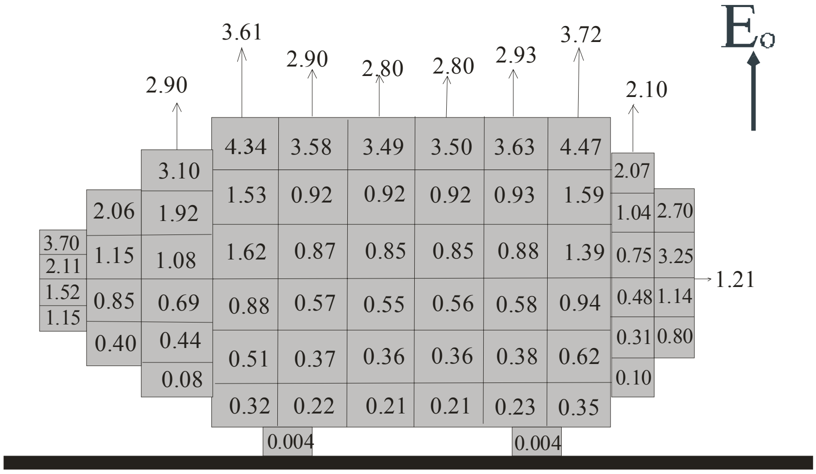

Fig. 2 - *Electric field enhancement factors for grounded pig.*

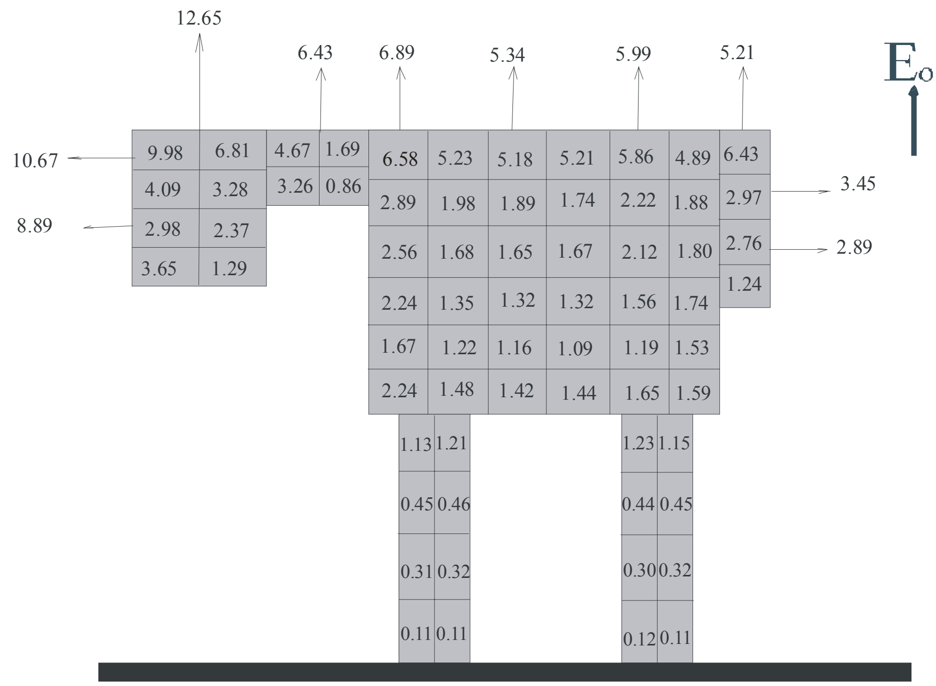

Fig. 3 - *Electric field enhancement factors for grounded baboon.*

The human body surface was partitioned into 344 subareas for symmetrical models to 1700 subareas for nonsymmetrical models. This method allows to analyze nonsymmetrical models too.

Detailed view of the electric field enhancement factor for a human model with the arms close to the body is presented in Fig. 4.

Detailed view of the electric field enhancement factor for human model with extended arms is presented in Fig. 5.

Detailed view of the electric field enhancement factor for human model with one arm close to the body and the other stretched to the front is presented in Fig. 6.

Detailed view of the electric field enhancement factor for human model with one arm close to the body and the other raised is presented in Fig. 7.

From Figs. 4, 5, 6 and 7 is evident that greater values of this factor exist for upper part of the body than for the lower one. The values of the enhancement factor on the legs and lower part of the body vary from 0.1 to 5.0, and on the head from 17.9 to 19.6 for different models. The largest values (28) are observed on the tip of the extended arms, on the end of the stretched arm (27.10) and on the tip of the raised arm (38) , due to its sharp geometry.

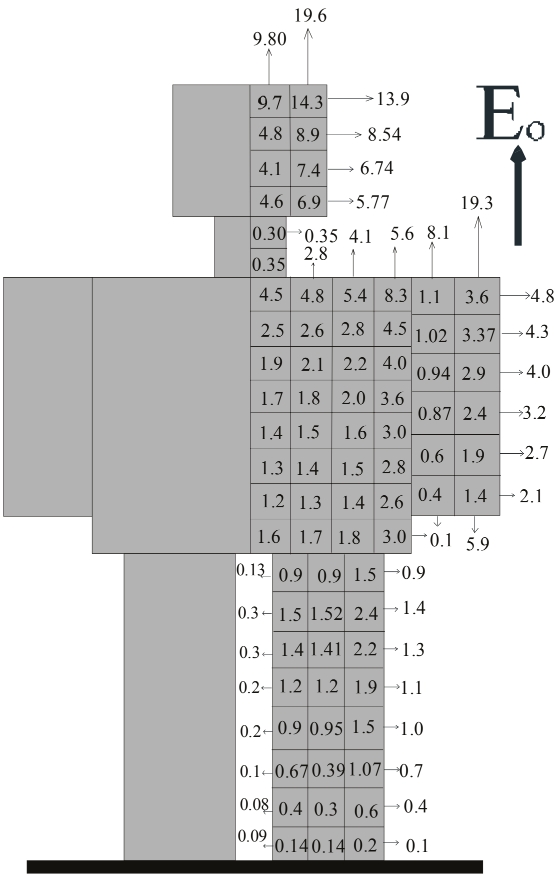

Fig. 4 - *Electric field enhancement factor for a human model with arms close to the body.*

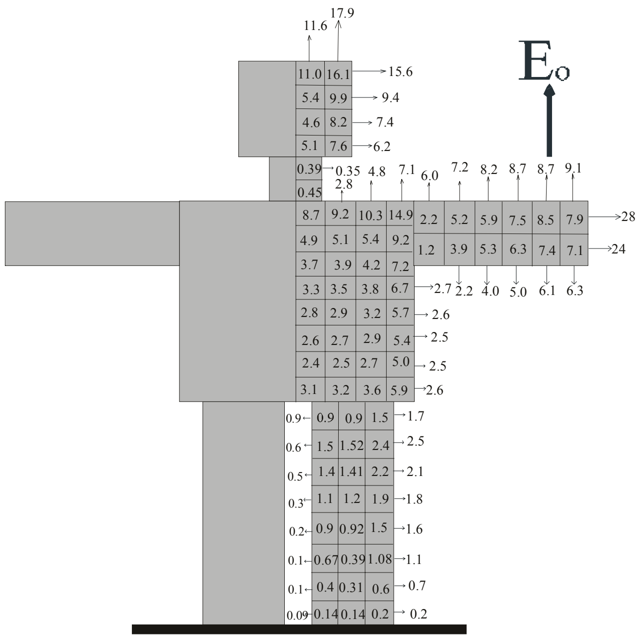

Fig. 5 - *Electric field enhancement factor for a human model with extended arms.*

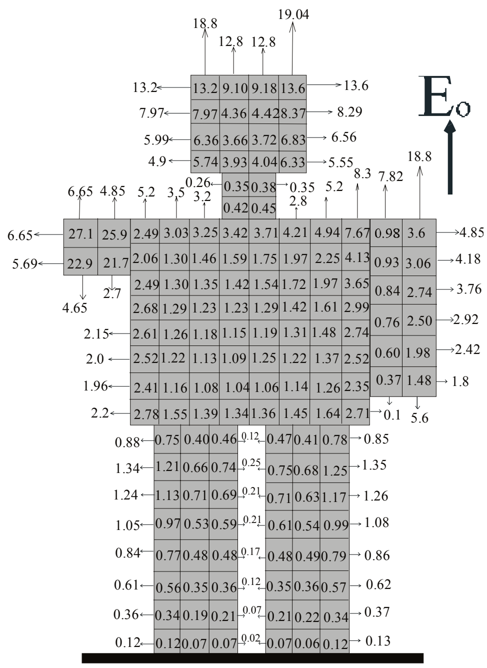

Fig. 6 - *Electric field enhancement factor for a human model with one arm close to the body and the other stretched to the front.*

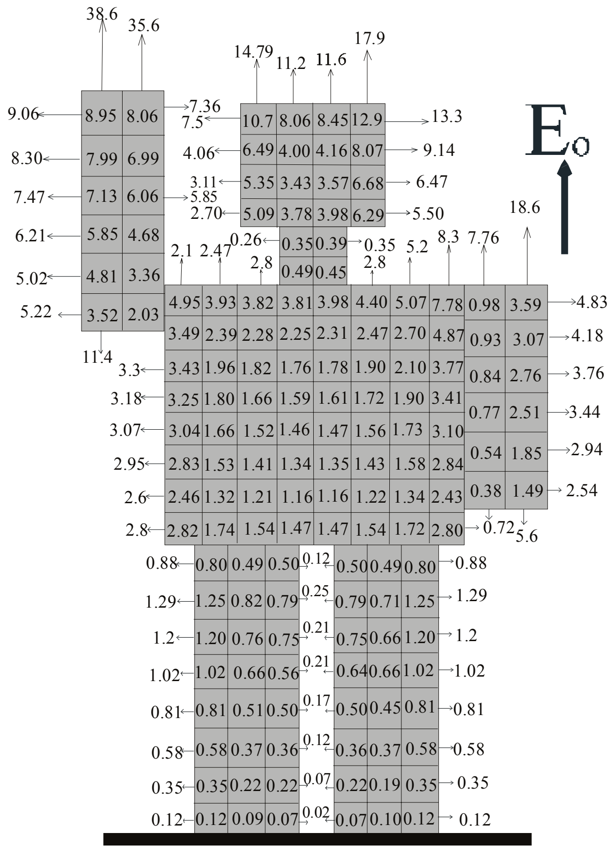

Fig. 7 - *Electric field enhancement factor for a human model with one arm close to the body and the other raised.*

We verified the accuracy of our method by comparing our results on the electric field enhancement factor on the body surface with numerical results by method of moments [3, 4]. The electric field enhancement factor on the surface of guinea pig [3] varies from 0.0034 to 3.6 at various points. The values of the enhancement factor vary from 0.1 to 20 over the body surface about realistic model of man standing on the ground, with arms close to the body, and that factor varies from 0.1 to 50 about realistic model of man with extended arms [3]. Same results by method of moments are presented in [4]. The values of the enhancement factor on the legs and lower part of the body vary from 0.1 to about 3.9, for the arms the enhancement factor can reach values of about 6.5, for the shoulders 16.5, but the largest values in this case are observed on the head and can reach 23. Above results are found for the model with arms close to the body [3]. For the model with extended arms, the enhancement factor varies from 6.0 on the shoulders to 55 on the tip of the arms [3]. Good agreement is obvious when our numerical results for the electric field enhancement factors on the body surface are compared with numerical results of method of moments.

3.2 Distribution of electric field

Distribution of electric field in the proximity of various biological subjects exposed to an electric field in the LF range is presented with map of equipotential lines and map of equienergetic curves.

Equipotential map in the proximity of the human body for the model with the arms close to the body is shown in Fig. 8.

Equipotential map in the proximity of the human body for the model with extended arms is shown in Fig. 9.

Equipotential map in the proximity of the human body for the model with one arm close to the body and the other streched to the front is shown in Fig. 10.

Equipotential map in the proximity of the human body for the model with one arm close to the body and the other raised is shown in Fig. 11.

Equipotential map in the proximity of the pig's body is shown in Fig. 12.

Equipotential map in the proximity of the baboon's body is shown in Fig. 13.

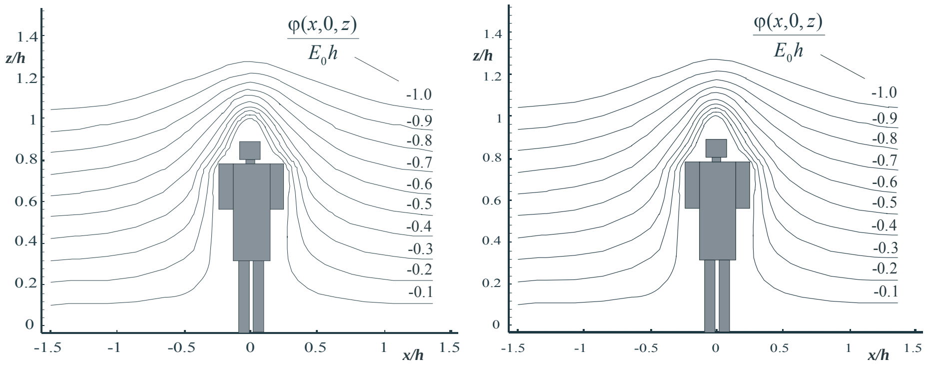

Fig. 8 - *Equipotential map in the proximity of the human body for model with arms close to the body.*

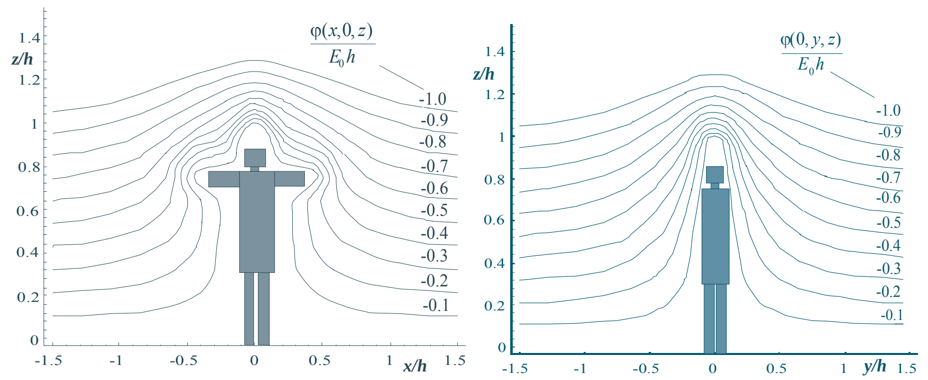

Fig. 9 - *Equipotential map in the proximity of the human body for model with extended arms.*

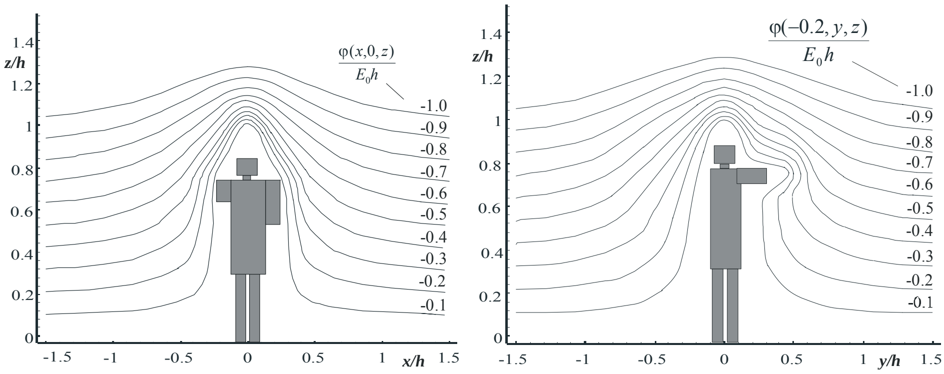

Fig. 10 - *Equipotential map in the proximity of the human body for model with one arm close to the body and the other stretched.*

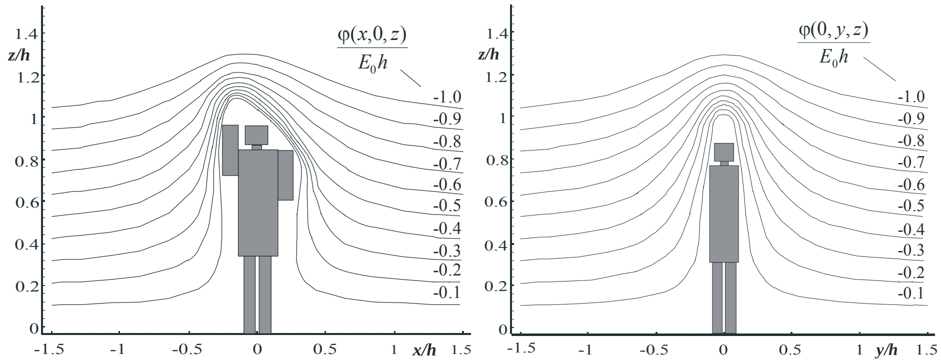

Fig. 11 - *Equipotential map in the proximity of the human body for model with one arm close to the body and the other raised.*

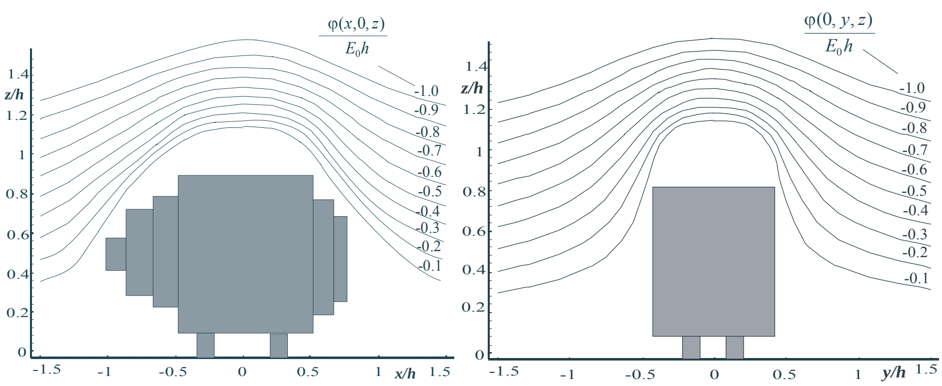

Fig. 12 - *Equipotential map in the proximity of the pig's body.*

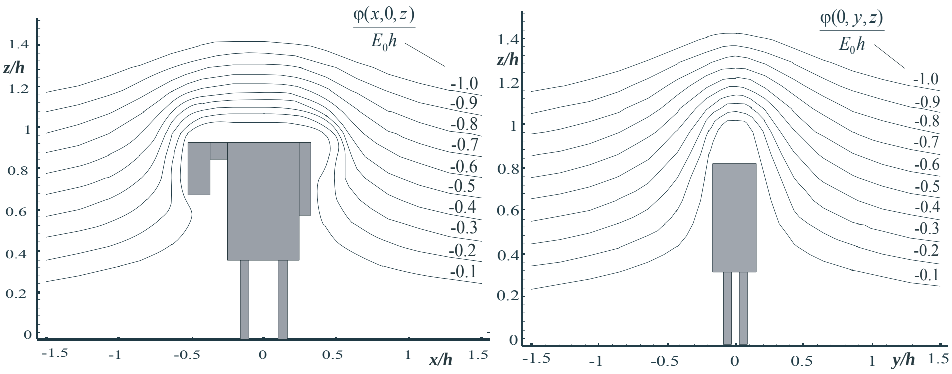

Fig. 13 - *Equipotential map in the proximity of the baboon's body.*

From above figures is evident that the impressed electric field, which is initially uniform, becomes distorted in the proximity of the human and animal bodies. The fields depend strongly on the shape of the body and its orientation relative to the electric field and to the ground plane.

Equienergetic curves in the proximity of the human body for the model with the arms close to the body is shown in Fig. 14.

Equienergetic curves in the proximity of the human body for the model with extended arms is shown in Fig. 15.

Equienergetic curves in the proximity of the human body for the model with one arm close to the body and the other stretched to the front is shown in Fig. 16.

Equienergetic curves in the proximity of the human body for the model with one arm close to the body and the other raised is shown in Fig. 17.

Equienergetic curves in the proximity of the pig's body is shown in Fig. 18.

Equienergetic curves in the proximity of the baboon's body is shown in Fig. 19.

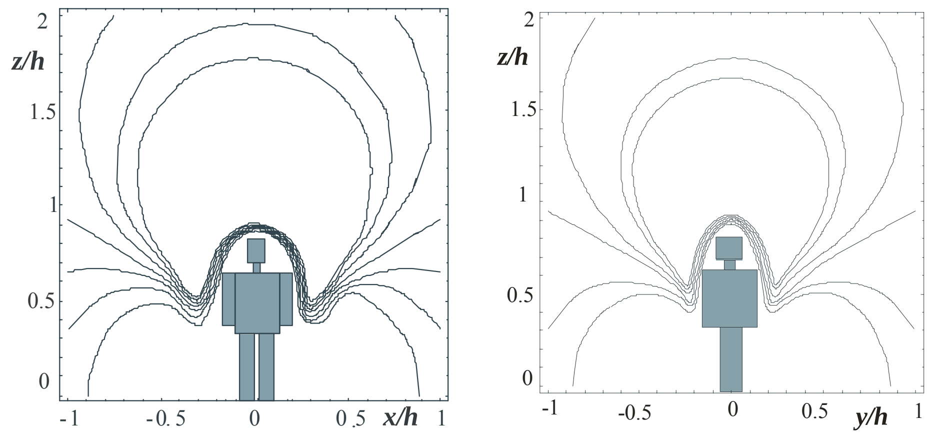

Fig. 14 - *Equienergetic curves in the proximity of the human body for model with arms close to the body.*

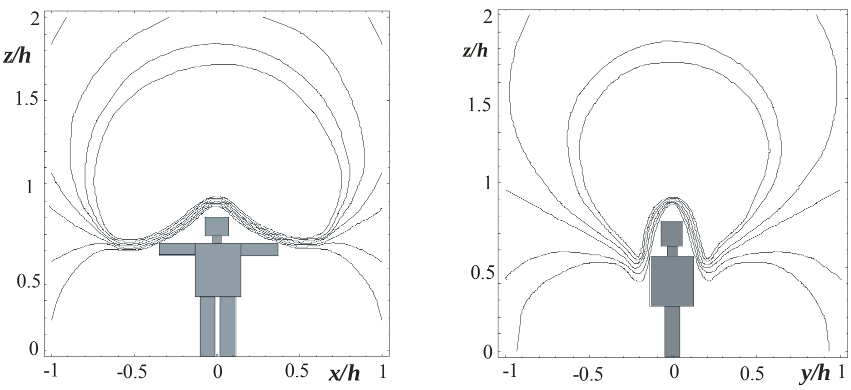

Fig. 15 - *Equienergetic curves in the proximity of the human body for model with extended arms.*

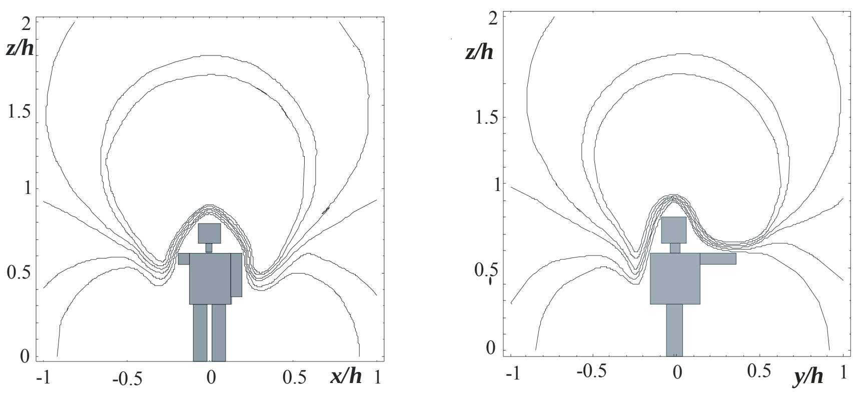

Fig. 16 - *Equienergetic curves in the proximity of the human body for model with one arm close to the body and the other stretched to the front.*

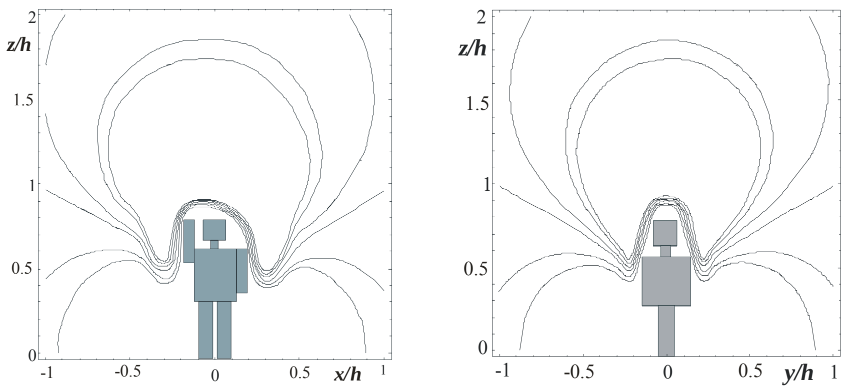

Fig. 17. - *Equienergetic curves in the proximity of the human body for model with one arm close to the body and the other raised.*

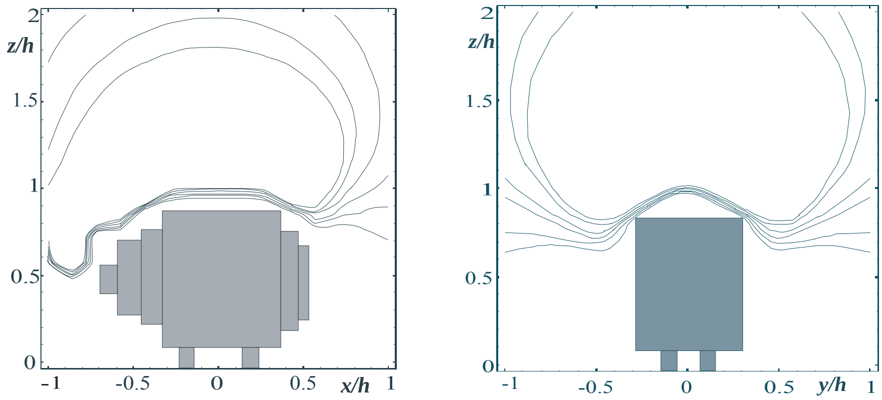

Fig. 18 - *Equienergetic curves in the proximity of the pig's body.*

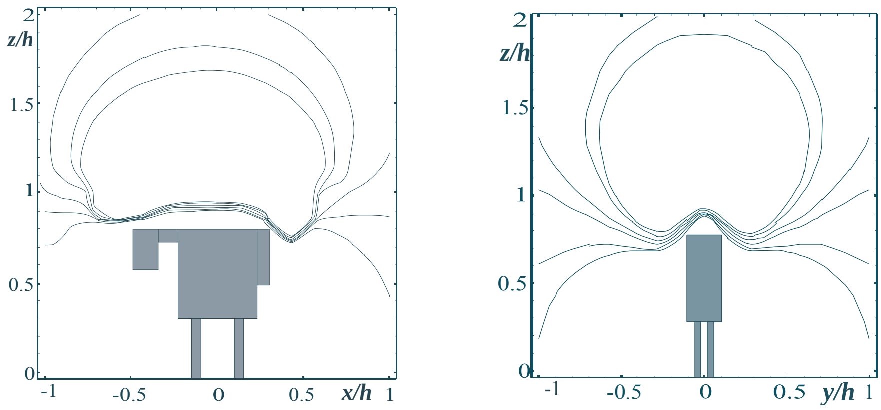

Fig. 19 - *Equienergetic curves in the proximity of the baboon's body.*

4 Conclusion

Different models of biological subjects are placed in uniform vertical electric field in LF range. It is presumed that the biological bodies are conductors, and the induced charges are distributed on their surface. With the boundary condition that biological subjects are grounded, it is possible to form integral equations for surface charge densities as unknowns. The equivalent electrodes method is used to solve these problems. Detailed views of the electric field enhancement factors on the body surface for different human and animal models are presented. Furthermore, equipotential maps and equienergetic curves in the proximity of various biological subjects are presented.

The produced results have demonstrated that induced charge density on the surface of the body and the field outside the body depends, only on the nature of the applied field, the shape of the body and the location and orientation of the body relative to the ground.

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