ELECTRIC FIELD DISTRIBUTION IN REALISTIC CELL SHAPE MODELS

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ABSTRACT

In order to study the mechanisms of direct cellular effects of RF exposure, this paper analyzes the important issue of a realistic modelling of cell shapes. For this purpose, the electric field within the membrane for the erythrocyte, rod cell and confocal and shelled ellipsoids geometries is calculated by using a finite element (FE) technique with adaptive meshing. Although mathematical calculations are greatly simplified using simple geometries instead of a more realistic cell geometry, the results show that for the erythrocyte like shape, the E field intensity is considerably higher than the value obtained for the ellipsoidal and rod models.

INTRODUCTION

The research about possible mechanisms of interaction of EM fields with biological tissues and cells in culture has motivated a growing need for accurate models describing the electric behaviour of cells exposed to these fields. Weak electric field effects have generally been attributed, at least as a primary event, to field interaction with either membrane or glycocalix constituents. The magnitude of transmembrane voltage and the deposited energy are basic issues for understanding the relation between the exposition to fields and the subsequent physiological reactions at the cell level.
Classical models of cells based on shelled spheres or ellipsoids were initiated by Fricke in 1925 [1] and have been used by many researchers since then for a variety of applications, ranging from predictions related to cell manipulation and trapping [2] to EM field microdosimetry studies [3]. They provide simple analytical solutions and make possible rationalize experimental results of impedance spectroscopy of cells, dielectrophoresis or electrorotation among others. However an explicit solution of Laplace equation requires a geometry consisting in one or several uniform media separated by interfaces which coincide with a surface of a constant coordinate, within a certain set of coordinate types [4].

This excludes other possible geometric configurations representing more realistic cell shapes, such as cylinders or rods. Even for ellipsoids, this constrain requires the surface of the membrane to be confocal with the main ellipsoid, producing a non uniform thickness. It is uncertain how this detail of modelling can affect the exactness of the predictions in the electric behaviour as the membrane is a site of a high field amplification. In fact, Gimsa [5,6] has warned about the use of confocal shells estimating that it may lead to large errors in the case of pronounced excentricity, For thin, low conductive shells, he has proposed a RC dumped element model instead. This model has the great advantage of simplicity and can be very useful when analyzing the physical origin of different dielectric relaxations shown by cells and for qualitative analysis of fields and forces. However, this model, in which a prismatic piece of dielectric medium is approximated by a simple RC circuit, seems to be valid only under the assumption of constant field and consequently, only for shells of vanishing thickness.

Therefore, it appears that only numerical methods can give a sufficiently precise estimation of field values in realistic cell anatomies. But up to date very few studies of this type have been reported [7], the main reason being the difficulty they have to face in handling regions of very different size scales: microns for the cell diameter and nanometers for the membrane thickness. As the numerical solution of Laplace equation in the form of finite differences involves a kind of polynomial approximation in nodes of a convenient grid, the existence of very small domains makes it necessary to use a very dense grid or alternatively sophisticated nonuniform meshing methods.

In this work we address the important issue of a realistic modelling of cell shapes to study the mechanisms of direct cellular effects of RF exposure. For this purpose, a powerful finite element (FE) technique with adaptive meshing has been developed to provide the electric field intensity within the membrane of the cell.

CELL SHAPES

Figure 1 shows the three different cell shapes that have been considered: erythrocyte, ellipsoidal (confocal and uniformly shelled) and rod as well as the selected geometrical and electrical parameters [7] for the different layers. For all three geometries, the cell structure is formed by two layers (cytoplasm and membrane) and the cell is immersed in a continuous medium formed by electrolytes in free water with the properties of physiological saline (ε_{r900} = 71.78, σ_{900} = 1.947 S/m, ε_{r2450} = 70.87 and σ_{2450} = 2.781 S/m). The frequencies of the RF radiation considered in this work are 900 and 2450 MHz.

In order to validate the FE numerical technique, an analytical solution was obtained for an ellipsoidal structure formed by two confocal homogeneous dielectric layers of revolution by using a quasistatic approximation. The use of this approximation can be justified, as the cell dimensions are very small compared with the wavelength at the frequencies used in this study. Table 2 shows a comparison of the normalized electric field intensity values within the membrane for confocal ellipsoids cell model provided by both the FE technique and the analytical approximation. The results are shown for vertical and horizontal orientations of the cell as to the applied field at 900 MHz. It is observed that the numerical computations are accurate, in the order of 2%. Table 2 shows the electric field intensity within the membrane at 900 and 2450 MHz obtained for confocal ellipsoids with an uniform thickness membrane of 10 nm and for both polarizations.

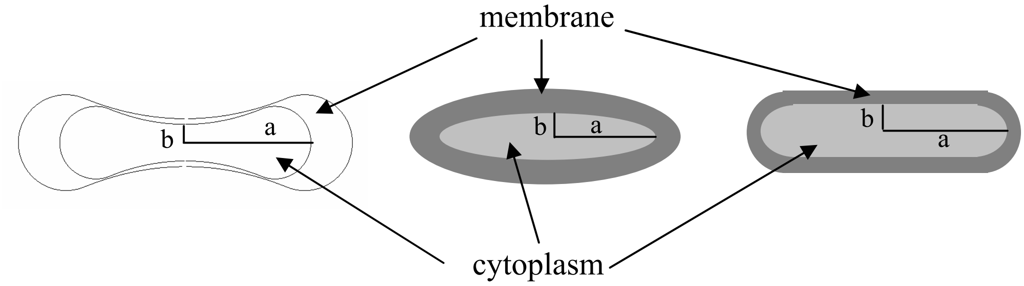

Fig. 1. Cross sections of the two-layer erythrocyte, ellipsoidal and rod cell models. Geometrical parameters: *a* =3.5 µm, *b* is variable from 0.5 to 1 µm. Electrical parameters of the membrane: σ = 0 S/m, ε_r = 11.3. Electrical parameters of the cytoplasm: σ_{900} = 0.99 S/m, ε_{r900} = 50.2, σ_{2450} = 1.417 S/m, ε_{r2450} = 48.699

Table 1. Analytical and numerical solutions for the normalized electric field within the membrane for confocal ellipsoids cell model at 900 MHz.

E Orientation ↑		
Analytical Solution	5.59	5.08
Numerical Solution	5.61	5.14

Table 2. Normalized electric field within the membrane for uniformly shelled and confocal ellipsoids.

Cell Type	Confocal		Shelled	
Normalized Electric Field in Membrane				
E Orientation ↑				
900 MHz	5.61	5.14	4.67	3.87
2450 MHz	5.41	4.85	4.44	3.53

It is observed in Table 2 that the orientation of elongated cells has an important influence in the value of the electric field. A higher value of E is found for the normal orientation for both confocal and shelled cells at 900 and 2450 frequencies. These results also confirm that the assumption of confocal ellipsoids cell models instead of uniformly shelled ellipsoids could lead to a significant error in the calculation of E field intensity.

Figure 2 shows a comparison of the electric field within the membrane for the erythrocyte, confocal ellipsoids and rod like cell geometries. In order to study the influence of the cell geometry on the E field, the value of the semi-axis *b* of the ellipsoidal and rod cells was varied from maximum (1μm) to minimum (0.5μm) width values of the erythrocyte. The electric field is applied along the semi axis *b* and the value of *a* = 3.5 μm was kept constant for all shape cells.

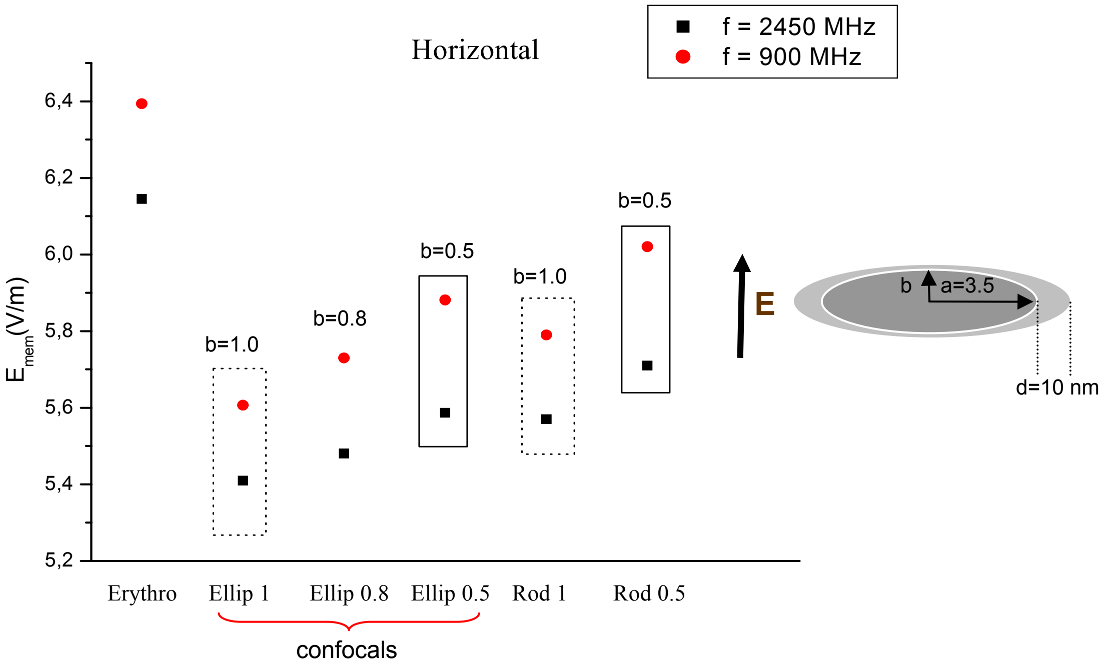

Fig. 2. Normalized electric field within the membrane for erythrocyte, confocal ellipsoids and rod cell shapes. Figures correspond to different values of geometrical parameter *b*.

Figure 2 also shows that, for the same value of semi-axis *b* (data inside rectangles), a rod geometry leads to a higher electric field within the membrane when compared with the ellipsoidal geometry. For the erythrocyte realistic shape, the E intensity is considerably higher than the one for the ellipsoidal and rod models for all values of parameter *b* in the range 0.5 to 1 μm

CONCLUSIONS

The different results presented in this paper show the influence of the cell geometry in the determination of the E field intensity within the membrane. Although confocal ellipsoids and rod like cell models, may help to simplify the mathematical calculations, their use as an approximation of a more realistic cell shape, such as the shape of an erythrocyte, leads to a lower value of the calculated E field.

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