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Analysis for Field Distribution in Bio-Tissues

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Abstract: *When the biological tissues are under the influence of EM fields, each tissue behaves differently as human body is non homogeneous. Each tissue is represented by its own fundamental media parameters i.e., permittivity, permeability and conductivity are different to each one of them. Zhao Wang reported detailed analysis on cellular scale, for single and double layer model of cell. It is of interest in the present work, we extend this analysis for additional tissues considering single layer models.*

Keywords: *conductivity, non homogeneous media, permeability, permittivity, single layer model.*

I. Introduction

Bioelectromagnetics in living organisms is an interdisciplinary subject, which studies the role of electromagnetic in biological processes correlating the biophysical and biochemical functions at the cellular level. In biological systems, cells and tissues are constantly subject to electromagnetic forces and fields, which could be due to molecular interactions and/or externally applied electromagnetic fields. As a result of these forces, physiological behaviors of cells could be modified; and in extreme cases, it could even put the entire system in danger. Therefore, in order to protect living organisms from excessive stress, it is critical to understand how they interact with electromagnetic fields (EMF) [1, 2].

When exposed to electromagnetic fields or waves, electromagnetic energy is induced or deposited. The fields are forces that act only with electric charges. The absorbed electromagnetic energy in the living body causes effects depending on parameters such as the energy (dose), the energy rate (dose rate), the field strength, the frequency (photon energy) of the fields and also of the type of tissue [3].

Electromagnetic fields interact with matter forces generated on charges. Internal electric fields act on bound and free charges in the body tissue causing polarization, molecular orientation and the establishment of ionic currents. There is little, if any, direct interaction with magnetic field, instead, time varying magnetic field generate electric fields with the usual consequences [4, 5].

Interaction between EM fields and people occur at all levels of organization. The coupling of external fields with the body is the first step leading to further interaction at the cellar and molecular level. The initial coupling is a function of numerous parameters including field characteristics as well as the size and shape of the body and its electrical properties. The coupling is most efficient when the size of the body is of the same order of magnitude as the wavelength of the field and when the long axis of the body is in the direction of the field [6].

Interaction can take place through either thermal or nonthermal mechanisms. Thermal mechanisms are those resulting from the temperature change of the tissue caused by the RF fields. They might, for example, produce changes in the rates of biochemical reactions since these are all likely to be temperature dependent to some degree. All interactions between RF fields and biological tissue are likely to result in energy transfer to the tissue and this will ultimately lead to an increase in its temperature. But nonthermal mechanisms are those that are not directly associated with this temperature change but rather to some other change produced in the tissue by the RF electric or magnetic field [7, 8].

The body tissues are organized systems of very small cells which are bathed in a watery fluid and packed in a protective skin. About two third of the body is water and roughly half of this is found outside the cells. The electromagnetic properties of the body depend on the fact that numerous ions are dissolved in this fluid and on the fact that water molecules are electric dipoles. Exposure of a biological cell to electric field can lead to a variety of biochemical and physiological responses. If the field is sufficiently strong, the exposure can cause a significant increase in the electric conductivity and permeability of the cell plasma membrane. Provided that the exposure is neither too strong nor too long, this phenomenon (referred to as electroporation or electropermeabilization) is reversible. Using electroporation, many molecules to which the cell plasma membrane is otherwise impermeable can be introduced into the cells or inserted into their plasma membrane.

Due to its efficiency, this method is rapidly becoming an established approach for treatment of solid cutaneous and subcutaneous tumors, and it also holds great promise for gene therapy. As a cell is exposed to an external field, this leads to an inducement of a voltage on the cell plasma membrane. This voltage is proportional to the field strength and superimposes onto the resting voltage present on the membrane under physiological conditions [9, 1].

All living organisms have a precise and delicate electromagnetic nature. All functions at cellular, tissue, and organ level are controlled by physiological endogenous electric fields like the trans-membrane electric fields, and corresponding weak transient endogenous electric currents, like the intracellular electric currents originating from cytoplasmic voltage differences due to corresponding differences in the concentrations of mobile ions within cells. Intracellular electric currents are found to control cell growth, proliferation, differentiation, etc, while corresponding electric currents within tissues involving hundreds/thousands of cells, control embryonic development, wound healing, or tissue regeneration [6, 3].

As a cell is exposed to an external field, this leads to an inducement of a voltage on the cell plasma membrane. This voltage is proportional to the field strength and superimposes onto the resting voltage present on the membrane under physiological conditions.

Both the potential health hazards and the promising applications of cell manipulation require understanding of biophysical phenomena of cells such as electroporation. Electroporation, an instantaneous pore formation on the cell plasma membrane, is principally controlled by the transmembrane potential, which is defined as the potential difference across the plasma membrane. Therefore, to understand the related phenomena, the electric field distribution and electric potential on the membrane need to be quantified inside and around cells [10].

In this paper, firstly, the model of the cell under exposure of the external illuminated EM field will be built. Biological cells were approximated by multi-layer spheres with homogeneous, lossy and dispersive dielectric properties for each layer [10]. For understanding of single layer model, first a Spherical double layer model is adopted for simplicity, as shown in Fig. 1.

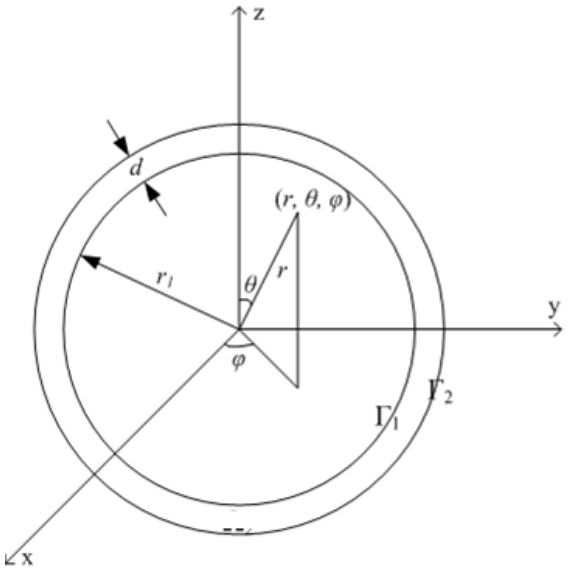

Figure 1 The spherical double-layer shell-model of a cell in 3-dimensional view. The point (r, θ, φ) is presented in spherical coordinate system. The parameters r_1 and d are the radius of cell and membrane thickness, respectively.

The cell under test is exposed to a linearly polarised plane wave with electric field intensity E_0 of 1V/m in the external medium, which is operating at 2GHz. The incident plane wave propagates along +z axis polarised in x-axis.

The problem of a biological cell exposed to RF electromagnetic fields is simplified into a simple or shelled-sphere immersed in a quasi-static electromagnetic field as shown in Figure 1. The dielectric properties of the compartment of the sphere and external medium are according to the literature reported values as presented in Table 1 [11].

In the present work, a single layer model which is shown in Fig. 2 is used for different tissues.

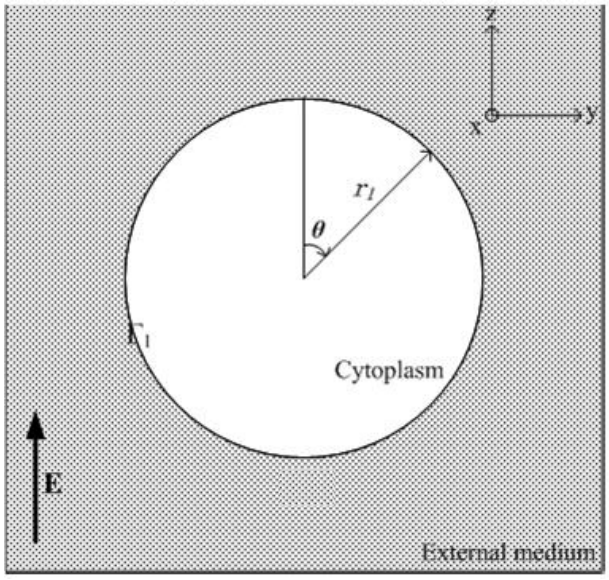

Figure 2: Spherical cell model exposed to uniform time-harmonic electric field: single layer cell model with radius *r1* and Γ1 is the interface between the two media.

II. Formulation

The internal and external media are characterised by the complex Permittivities.

$$\bar{\epsilon} = \epsilon_0 \left[\epsilon_r - j\frac{\sigma_r}{\omega\varepsilon_0}\right] \quad (1)$$

Where

$\mathcal{E}_0$ is absolute permittivity of free space.

$\mathcal{E}_r$ is relative permittivity of the medium.

σ_r is the conductivity of the medium.

and the potential due to the external electric field $\bar{E} = E_0\,\hat{z}$ is $V_0 = -E_0 z$
which can be expressed as $V_0 = -E_0 r\cos\theta$ in spherical coordinates.

For the sake of completeness, the solution of Laplace equation is presented below .In spherical coordinates, Laplace equation is given by

$$V = F_1(r)F_1(\theta)F_3(\emptyset) \quad (2)$$

Where V is the potential in scalar function .Using the boundary conditions the solution is given by

$$V(r,\theta) = \sum_{n=0}^{\infty} A_n\, r^n P_n(\cos\theta) + \sum_{n=0}^{\infty} B_n r^{-(n+1)} P_n(\cos\theta) \quad (3)$$

By using boundary conditions, the solution to one layer sphere can be obtained from calculations.
One layer sphere :
Equation (2) presents the general solution of Laplace's equation, which needs some modification to remain regular at the special points.
At any interior point, the coefficients Bn in (2) are set to zero to keep regularity at $r = 0$. Therefore, the resulting potential is:

$$V^- = \sum_{n=0}^{\infty} a_n\, r^n P_n(\cos\theta) \qquad (r \le r_1) \quad (4)$$

The potential outside the sphere consists of two parts. One is the primary external potential V0, and the other part (V1+), is due to induced charge density on the interface between two media.
There are shown in (4) and (5)

$$V_0 = -E_0 z = -E_0 r\cos\theta = -E_0 r P_1(\cos\theta) \quad (5)$$

$$V_1^+ = \sum_{n=0}^{\infty} b_n \frac{P_n(\cos\theta)}{r^{n+1}} \quad (r \le r_1) \quad (6)$$

Therefore, the potential outside the sphere is

$$V^+ = -E_0 r P_1(\cos\theta) + \sum_{n=0}^{\infty} b_n \frac{P_n(\cos\theta)}{r^{n+1}} \quad (r \le r_1) \quad (7)$$

On the interface Γ1 between two media, the boundary conditions give two equations.

$$V^+ = V^- \quad (8)$$

$$\tilde{\epsilon}_2 \frac{\partial V^+}{\partial r} = \tilde{\epsilon}_1 \frac{\partial V^-}{\partial r} \quad (r = r_1) \quad (9)$$

Where $\tilde{\epsilon}_1$ and $\tilde{\epsilon}_2$ are complex permittivities of single layer cell and external medium
The resultant potentials are

$$V^- = -\frac{3\tilde{\epsilon}_2}{\tilde{\epsilon}_1 + 2\tilde{\epsilon}_2} E_0 r\cos\theta \quad (r \le r_1) \quad (10)$$

$$V^+ = -E_0 r\cos\theta + \frac{\tilde{\epsilon}_1 - \tilde{\epsilon}_2}{\tilde{\epsilon}_1 + 2\tilde{\epsilon}_2} r_1^3 E_0 \frac{\cos\theta}{r^2} \quad (r > r_1)$$

Within the sphere, the field is parallel and uniform:

$$E^- = -\frac{\partial V}{\partial z} = \frac{3\tilde{\epsilon}_2}{\tilde{\epsilon}_1 + 2\tilde{\epsilon}_2} E_0 = -\alpha_1 \quad (r \le r_1) \quad (11)$$

The field outside is

$$E^+ = E_0 + \frac{\tilde{\epsilon}_1 - \tilde{\epsilon}_2}{\tilde{\epsilon}_1 + 2\tilde{\epsilon}_2} \frac{2r_1^3}{r^3} E_0 = E_0 + \frac{b_1}{r^3}(3\cos^2\theta - 1) = E_0 + \frac{2b_1}{r^3} \quad (r > r_1) \quad (12)$$

Table 1: Permittivity (ϵ_r) and conductivity (σ_r) values of different tissues at 2GHz [11]

Tissue	ϵ_r(farad/m)	σ (mho/m)
Muscle (Transverse fiber)	53.29	1.453851
Blood	59.02232	2.186298
Skin(dry)	38.5679	1.265463
Fat	5.327579	0.085915
Bone(cortical)	11.653735	0.310047
Kidney	53.85193	2.089864
Liver	43.82147	1.403848
Skin(wet)	43.52045	1.335596
Small Intestine	55.40508	2.83367
Eye Tissue (Sclera)	53.27029	1.724382
Breast Fat	5.23233	0.106125

III. Results

In this paper the values of relative permittivity and conductivity at 2GHz are presented in table 1.By using these values the complex permittivity of different tissues are calculated by using equation (1). Electric field distribution with in the cell of radius 10μm surrounded by external medium for single layer cell model shown in fig(2) along the axis parallel to external field when external field E_0=1V/m for 2GHz for different tissue combinations by using equations (11) and (12) is plotted. The resultant waveforms are shown in Fig. 3 to 16.

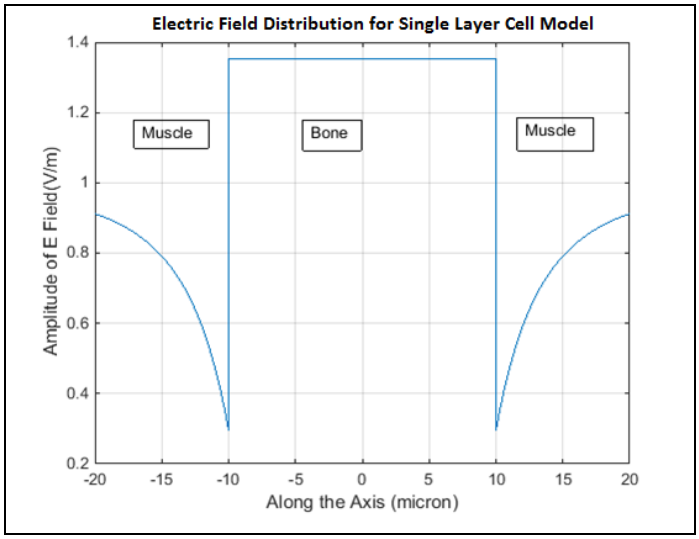

Fig. 3: Electric field distribution with in bone cell surrounded by muscle tissue at 2GHz

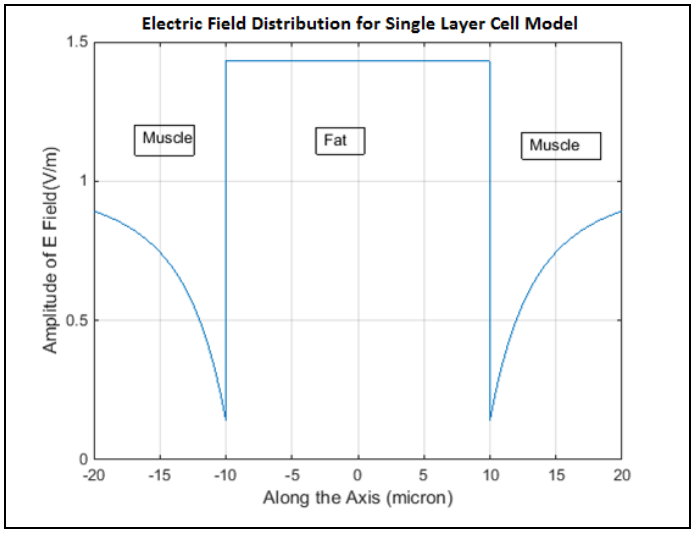

Fig. 4: Electric field distribution with in fat cell surrounded by muscle tissue at 2GHz

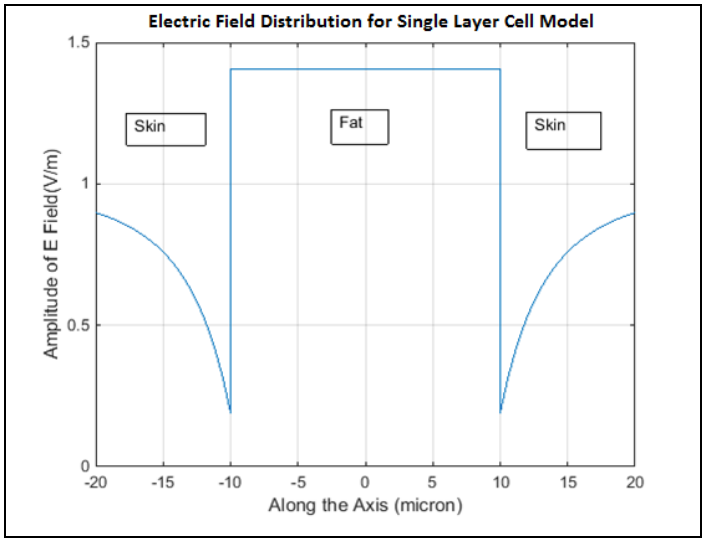

Fig. 5: Electric field distribution with in fat cell surrounded by skin tissue at 2GHz

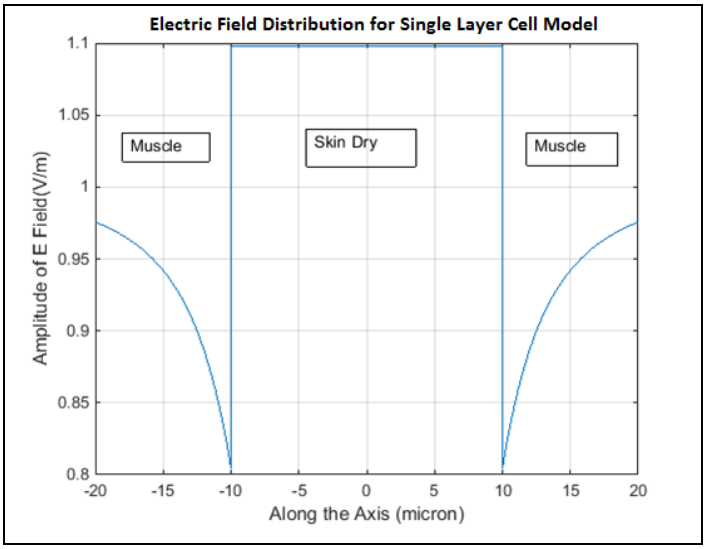

Fig. 6: Electric field distribution with in skin(Dry) cell surrounded by Muscle tissue at 2GHz

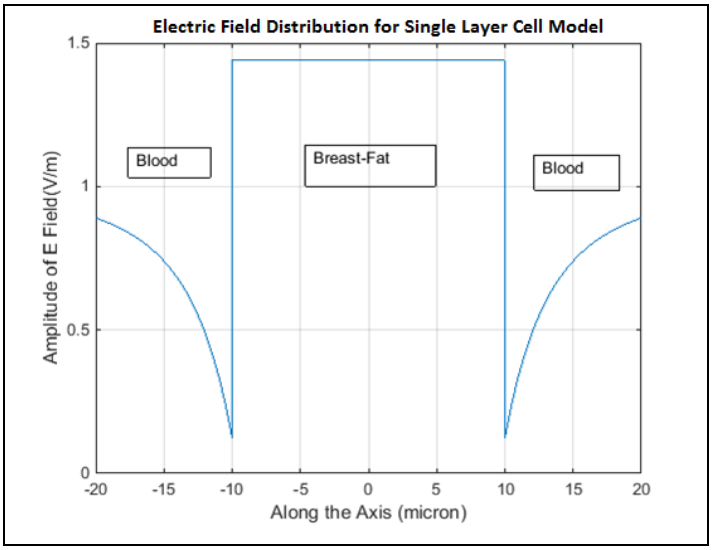

Fig. 7: Electric field distribution with in Breast_fat cell surrounded by blood tissue at 2GHz

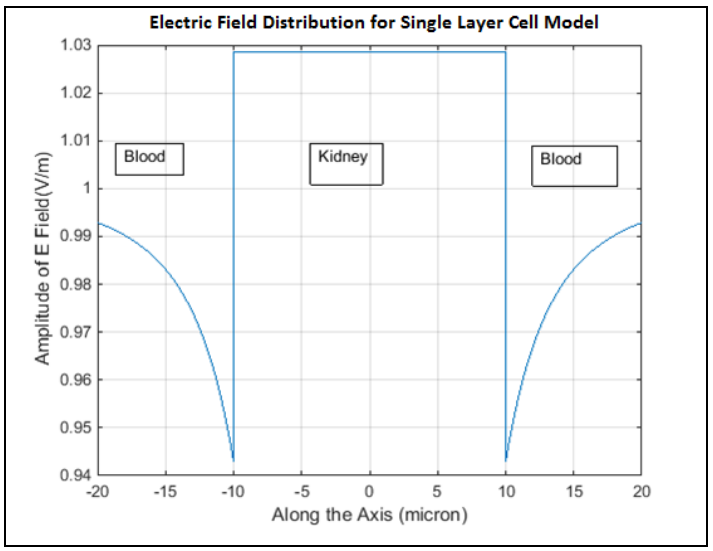

Fig. 8: Electric field distribution with in kidney cell surrounded by blood tissue at 2GHz

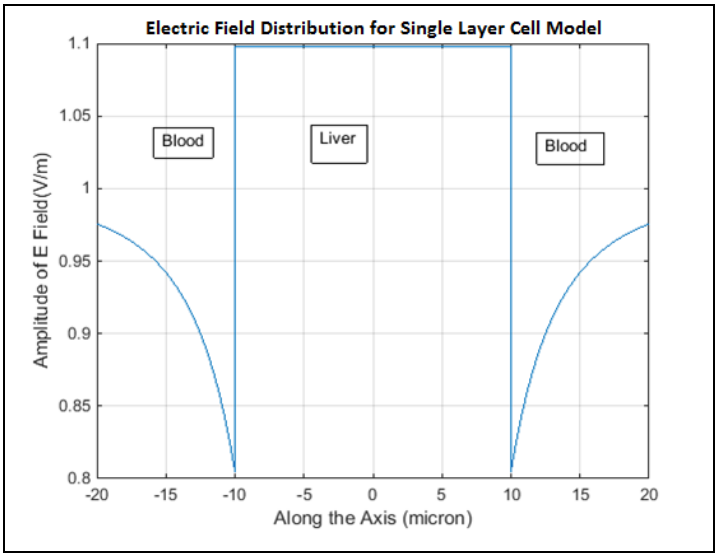

Fig. 9: Electric field distribution with in liver cell surrounded by blood tissue at 2GHz

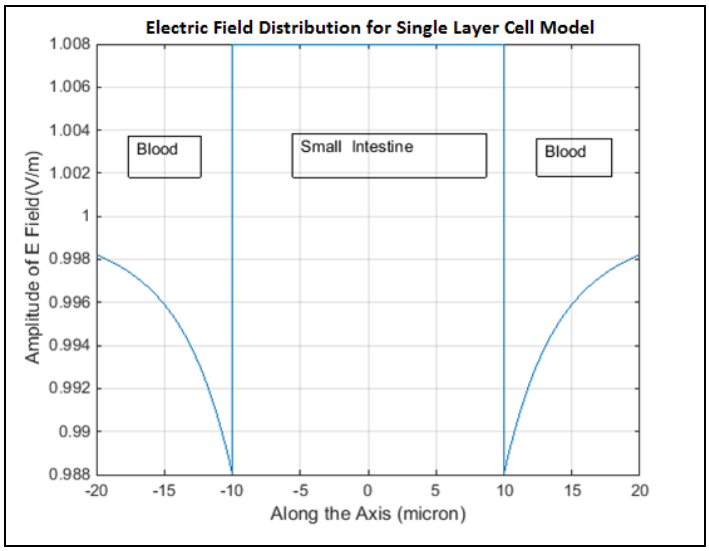

Fig. 10: Electric field distribution with in small intestine cell surrounded by blood tissue at 2GHz

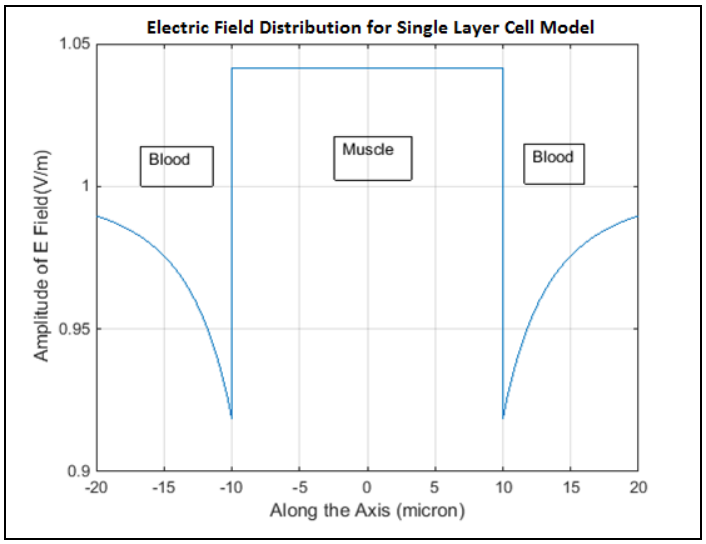

Fig. 11: Electric field distribution with in muscle cell surrounded by blood tissue at 2GHz

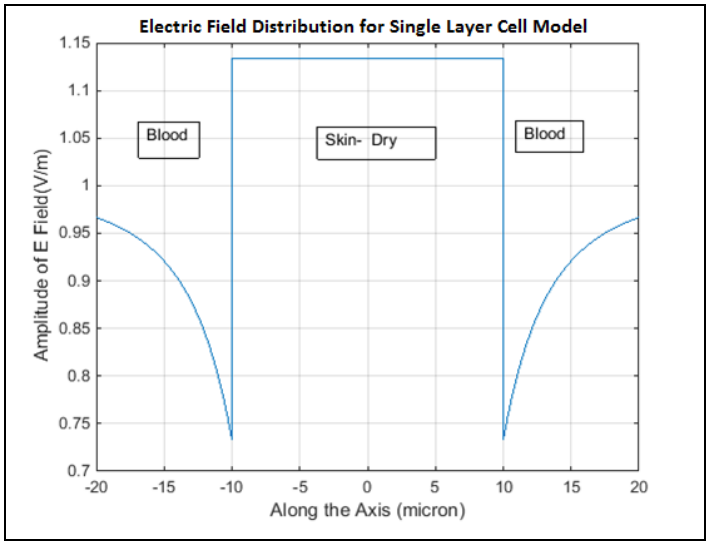

Fig. 12: Electric field distribution with in skin_dry cell surrounded by blood tissue at 2GHz

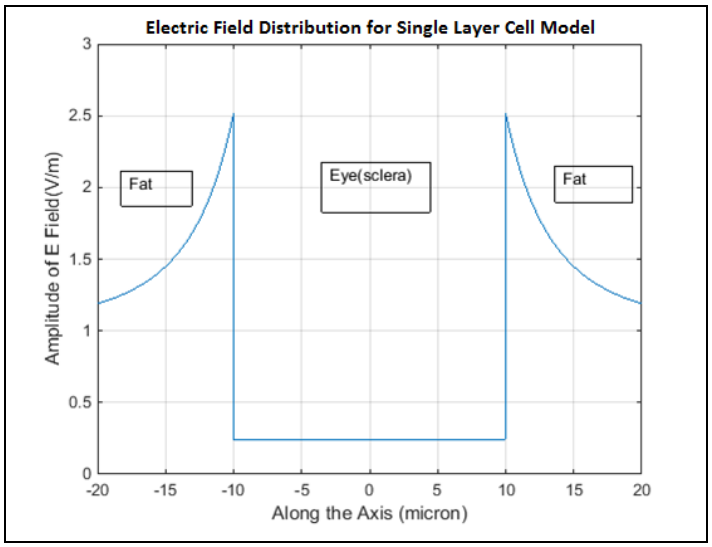

Fig. 13: Electric field distribution with in Eye(sclera)cell surrounded by fat tissue at 2GHz

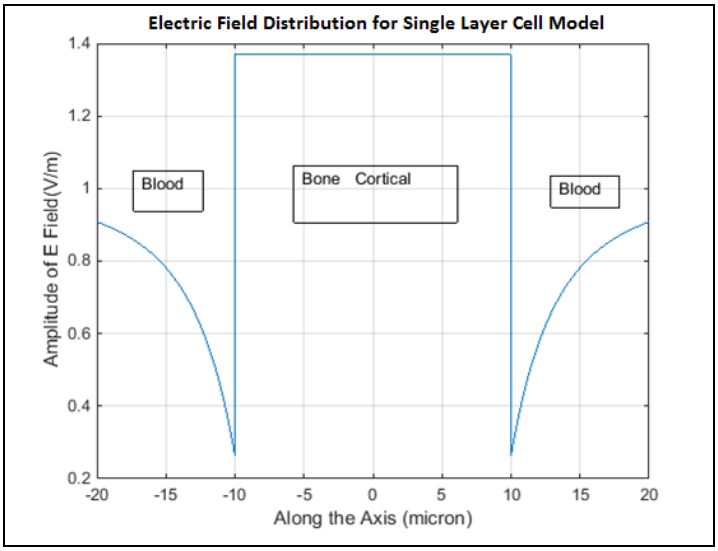

Fig. 14: Electric field distribution with in bone_cortical cell surrounded by blood tissue at 2GHz

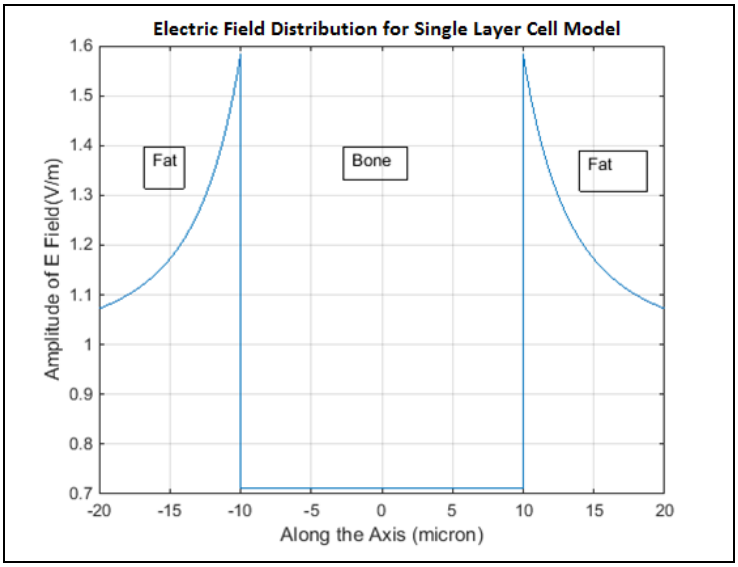

Fig. 15: Electric field distribution with in bone cell surrounded by fat tissue at 2GHz

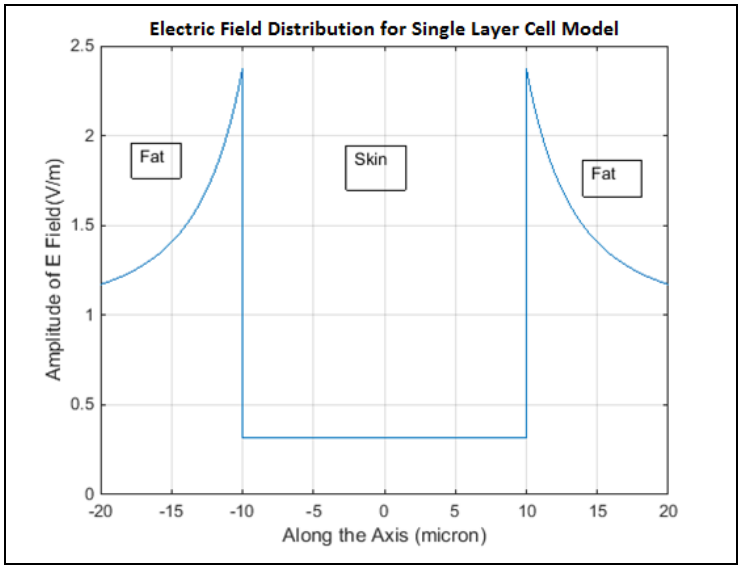

Fig. 16: Electric field distribution with in skin cell surrounded by fat tissue at 2GHz

IV. Conclusions

Electric field is estimated along the axis of the tissue using Laplace equation. It is observed that the field inside the cell is higher than the incident intensity and field outside the cell is lower than incident field, when dielectric constant of the internal cell is lower than the external medium. Otherwise it will be reversed.

When bone is surrounded by muscle tissue as shown in Fig. 3, the amplitude of electric field starts at 0.9V if radius is at -20 micron i.e., in muscle tissue and decreases to 0.3V at -10micron radius. And when cell radius is from -10 to +10 micron, i.e., in the bone cell, the amplitude of electric field will raise to 1.38V and is constant over that range. When the radius is between 10 to 20 microns, i.e., in muscle tissue, the amplitude of electric field increases from 0.3V to 0.9V.

When fat is surrounded by muscle tissue as shown in Fig. 4, the amplitude of electric field starts at 0.9V if radius is at -20 micron i.e., in muscle tissue and decreases to 0.2V at -10micron radius. And when cell radius is from -10 to +10 micron, i.e., in the bone cell, the amplitude of electric field will raise to 1.48V and is constant over that range. When the radius is between 10 to 20 microns, i.e., in muscle tissue, the amplitude of electric field increases from 0.2V to 0.9V.

When fat is surrounded by skin tissue as shown in Fig. 5, the amplitude of electric field starts at 0.9V if radius is at -20 micron i.e., in skin tissue and decreases to 0.2V at -10 micron radius. And when cell radius is from -10 to +10 micron, i.e., in the fat cell, the amplitude of electric field will raise to 1.4V and is constant over that range. When the radius is between 10 to 20 microns, i.e., in skin tissue, the amplitude of electric field increases from o.2V to 0.9V.

When skin_dry cell is surrounded by muscle tissue as shown in Fig. 6, the amplitude of electric field starts at 0.975V if radius is at -20 micron i.e in muscle tissue and decreases to 0.8V at -10 micron radius. And when cell radius is from -10 to +10 micron, i.e., in the skin_dry cell, the amplitude of electric field will raise to 1.1V and is constant over that range. When the radius is between 10 to 20 microns, i.e., in muscle tissue, the amplitude of electric field increases from o.8V to 0.875V.

Similarly for other tissue combinations, electric field distribution is observed as shown in Fig. 7 to 16.

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