MODELLING OF THE MECHANISMS OF ELECTROMAGNETIC FIELDS INTERACTION WITH HUMAN BODY

RAKOTOMANANJARA David Fitiana [1], RANDRIAMITANTSOA Paul Auguste [2],

[1] *PhD Student, Telecommunication Automation Signals Images, ED-STII, Antananarivo, Madagascar*
[2] *Professor, Telecommunication Automation Signals Images, ED-STII, Antananarivo, Madagascar*

ABSTRACT

The interactions of electromagnetic waves with the human body are complex and depend on several factors related to the characteristics of the incident wave such as: frequency, intensity, modulation and polarization, the proprieties of the tissue encountered (geometry, electrical properties: dielectric permittivity and conductivity), the type of coupling between the field and the exposed body and the duration of exposure. The irradiating field generates currents inside the body at extremely low frequency, and energy absorption in the tissues in RF and microwave range. Specific Absorption Rate (SAR) is the quantity that measure the rate of change of the energy transferred to the biological tissue. At a certain level of the irradiating field, the absorbed energy can cause heating of tissues and organs; this effect is well known as thermal effects. Another so-called non-thermal effect refers to the fact that biological effects can exist below the levels which produce the thermal effects. The great puzzle here is firstly, whether radiation at such low levels can cause harmful biological changes without a confirmable thermal effects, and secondly, whether such effects can occur from electromagnetic fields radiation when thermoregulation maintains the body temperature at the normal level despite the electromagnetic energy deposition, or when thermoregulation is not challenged and there is no significant temperature change. In this article we will detail the mechanisms of interactions of electromagnetic waves with the human body from its sources, the propagation and zone of exposure, the penetration of the waves into the biological tissue, the mechanism of interaction with the tissue and the corresponding possible biological effects.

Keyword: - *Biological media, Coupling, SAR, skin depth, thermal effects, non-thermal effects, VGCC*

1. INTRODUCTION

When a biological entity is exposed to electromagnetic radiation, interactions occur with the electrical charges of tissues or cells. These interactions can cause biological effects which are not necessarily harmful to health. The complexity of these phenomena is due to several factors, in particular the characteristics of the incident wave: its frequency, polarization and intensity.

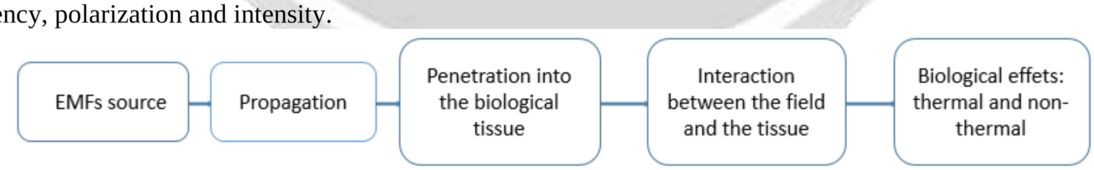


Fig -1: process of mechanism of interactions of EMFs with human body

This article is organized by following the process of wave interaction with living things as shown in Figure 1. We will begin with a description of the sources of electromagnetic fields to which we are exposed every day, then characterize the propagation and zone of exposure from the sources (antennas).In part 3 and 4, we will explain the mathematical models that govern the electromagnetic fields penetration in the tissue and the interaction between them. Finally, in part five, we will detail the mechanism of thermal effects and the hypothesis behind non-thermal effects.

2. ELECTROMAGNETIC WAVES AND SPECTRUM

Mankind is always exposed to electric, magnetic and electromagnetic fields, both from natural and artificial source:

- The permanent electric field from the potential difference of 300 kV between the ground and the ionosphere

- The magnetic field that encircles the Earth, from the North Pole to the South Pole
- infrared rays radiated by all heat sources, light, ultraviolet rays,
- Electromagnetic fields from electrical energy, telecommunications, medical device (like Magnetic Resonance Imagery)…etc.

The spectrum of electromagnetic radiation represents the distribution of electromagnetic waves as a function of their wavelength, their frequency or even their energy. It ranges from 0 Hz to infinity. It is important to clearly distinguish that the electromagnetic wave is a model used to represent the electromagnetic radiations which are the phenomenon studied. Electromagnetic radiation is a form of energy transport without physical support.

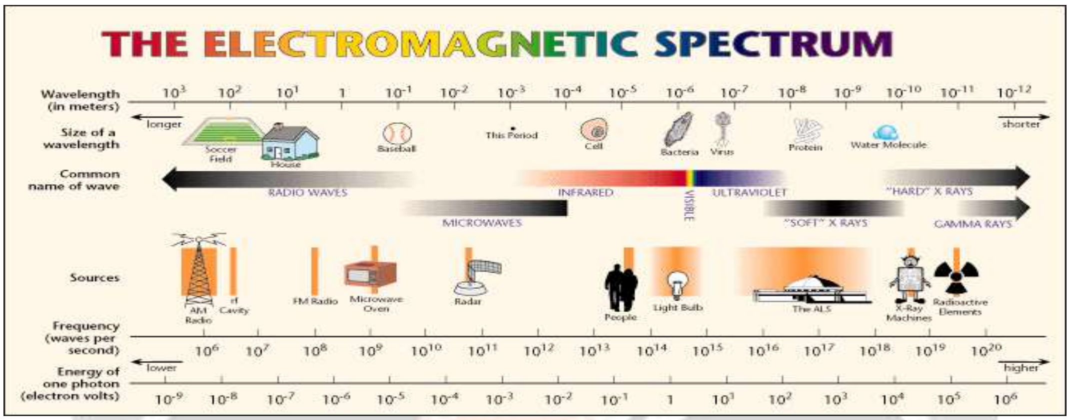


Fig -2: Electromagnetic spectrum [2]

The energy of electromagnetic waves is quantized with the quantum of energy (in joules), thus each photon carries a quantum of energy proportional to the frequency of the electromagnetic wave considered as described by relation (1) this energy is all the greater as the frequency is high.

$$E = hf \tag{1}$$

Where

- E is the energy of the electromagnetic wave [J],
- *h* Planck constant (h = 6.63 × 10-34 J s)
- *f*: frequency of the wave (Hz)

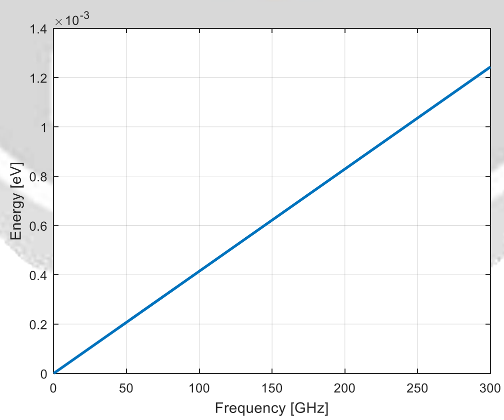


Fig -3: Electromagnetic wave energy from 0 Hz to 300 GHz

Ionization is the action of removing or adding charges to an atom or molecule. The ionization potential or ionization energy of an atom or a molecule is the energy that must be supplied to a neutral atom to tear off an electron (the least bound) in the gaseous state and form an ion positive. Typically, the ionization potential is on the order of 10 eV. For example, for the hydrogen atom, the ionization potential is 13.6 eV [2]. Figure 3 shows that even electromagnetic waves up to 300 GHz (used for electricity and telecommunications systems) have only weak energies to produce ionization.

3. ELECTROMAGNETIC WAVES RADIATION

An electromagnetic waves propagate at the speed of light and in an outward direction with respect to their origin. This process is referred to as radiation. A source of electromagnetic radiation radiates electric and magnetic fields whose spatial configuration and amplitudes differ depending on the distance between the antenna and the point of observation. In general, as illustrated in figure 4, three distinct zones are considered and defined with respect to the operating wavelength:

- The reactive near field zone: in the immediate vicinity of the antenna, the fields are purely reactive. This indicates that electromagnetic energy is completely stored and the electric and magnetic field are completely out of phase. is a very "thin" area that is less than $\frac{\lambda}{2\pi}$ from the antenna: within this zone, the waves are evanescent and the propagation phenomena are negligible compared to the radiative phenomena
- The radiating near field is composed of two zones: the Rayleigh zone and the Fresnel zone. The Rayleigh zone is at distance from the antenna between $\frac{\lambda}{2\pi}$ and $\frac{D^2}{2\lambda}$, D being the largest dimension of the electromagnetic antenna confined in a cylinder around the radiating aperture. The Fresnel zone is an intermediate zone located between $\frac{D^2}{2\lambda}$ and $\frac{2D}{\lambda}$
- The Fraunhofer zone lies beyond $\frac{2D^2}{\lambda}$ and is called the far-field area of the antenna. The reactive fields become negligible and the radiating fields dominate. The radiated energy is confined in a conical beam and the waves are locally almost plane; that is to say that the electric field and the magnetic field are in phase and that the ratio of their amplitudes is constant. In addition, the electric field and the magnetic field are perpendicular to each other and are located in a plane perpendicular to the direction of propagation. In vacuum the magnetic field H (A / m) and electric field E (V / m) are related by the relation (2)

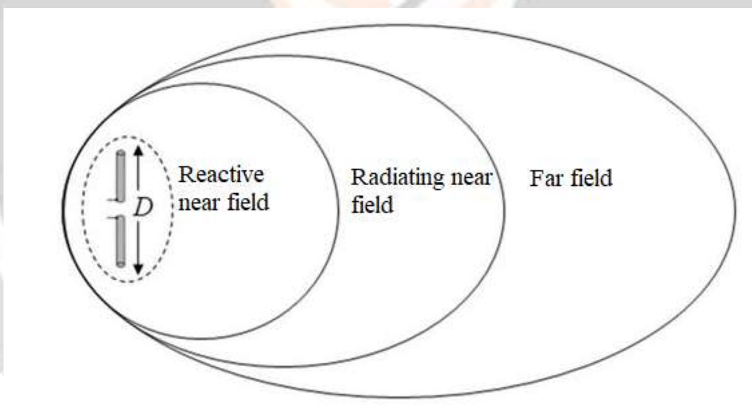


Fig. 4: different field regions

$$H = E/Z_0 \qquad (2)$$

$Z_0 = 377\Omega$ is the free space characteristic impedance

3. ELECTROMAGNETIC WAVES PENETRATION IN BIOLOGICAL TISSUES

In [2], we can see that the biological media lie between the dielectric and the conductor. The bases of all electromagnetic interactions with materials have long been elucidated by Maxwell's equations, however the difficulty lies in their application with living systems. Living organisms are extremely complex and have multiple levels of organization.

2.1 Maxwell's equations

All electromagnetic phenomena can be described by Maxwell's equations. These equations make it possible to relate the electromagnetic field to the sources which gave it birth. In fact, these four equations are split into two groups of two equations: the first group translates the intrinsic properties of the field (independently of the sources) and the second really informs about the dependence of this one regarding the sources.[3]

$$\vec{\nabla} \times \vec{E} = -\frac{\partial}{\partial t}\vec{B} \quad (3)$$

$$\vec{\nabla}.\vec{B} = 0 \quad (4)$$

$$\vec{\nabla}.\vec{D} = 0 \quad (5)$$

$$\vec{\nabla} \times \vec{H} = \vec{J} + \frac{\partial}{\partial t}\vec{D} \quad (6)$$

Where

- $\vec{E}$: electric field [V/m]
- $\vec{D}$:electric displacement field [C/m^2]
- ε_0=8.85 10^{-2} the permittivity of the vacuum, ε_r the relative permittivity of the dielectric
- ε: absolute permittivity [C /Vm]

$$\vec{D} = \varepsilon_0 \varepsilon_r \vec{E} = \varepsilon\vec{E} \quad (7)$$

- $\vec{B}$:magnetic induction field [Wb / m^2]
- $\vec{H}$: magnetic field [A/m]

$$\vec{B} = \mu_0 \mu_r \vec{H} = \mu\vec{E} \quad (8)$$

- μ: absolute magnetic permeability
- $\mu_0 = 4\pi.10^{-7}$ [H/m] vacuum permeability, μ_r relative permeability of a material
- J : current density [A/m^2]

The relations (7) and (8) introduce the characteristics of materials into the problem. Indeed, the electrical permittivity provides a description of the macroscopic interaction between the vector of intensity of the electric field and the dielectric material, while the magnetic permeability describes the interaction of the material with the magnetic field. For an exhaustive analysis of the electromagnetic problem defined by a radiating source and an exposed body, we will have to solve the Maxwell equations.

2.2 Electromagnetic waves propagation characteristics in biological media

In a biological medium the wavelength of the signal is given by the relation (9) [4]

$$\lambda = \frac{\lambda_0}{\sqrt{\frac{\varepsilon^*}{2}\left[\sqrt{1+\frac{\sigma^2}{\varepsilon^2\omega^2}}+1\right]}} \quad (9)$$

λ_0 is the wavelength in the free space

When a material is exposed to an electromagnetic field, it is subjected to a current density due to the movement of charges. Biological materials are not good conductors. Indeed, they conduct a current, however the losses can be significant, and they cannot be described as lossless. This is because the electromagnetic field only penetrates very superficially inside a conductor.

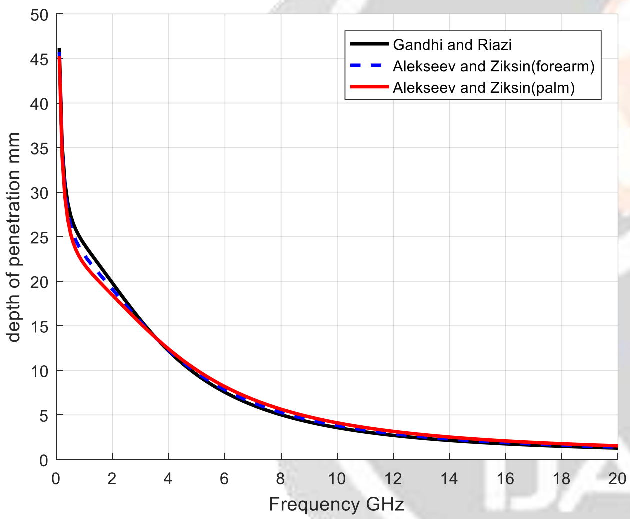
The depth of penetration (skin depth) δ is the distance over which the field decreases to 1/e (=0.368) of its value just inside the boundary is given by relation (10)

$$\delta = \frac{1}{\omega\sqrt{\frac{\varepsilon\mu_0}{2}\left[\sqrt{1+\frac{\sigma^2}{\varepsilon^2\omega^2}}-1\right]}} \quad (10)$$

Figure 4 and 5 illustrate the penetration depth of electromagnetic wave propagating into human skin. The skin was modelled using Debye single relaxation parameters from table-1

Table -1: skin permittivity parameters [5]

authors	ε_h	ε_l	τ	σ_s
Gandhi and Riazi	4	42	6.9 ps	1.4 S/m
Alekseev and Ziskin (forearm)	4	36.4	6.9 ps	1.4 S/m
Alekseev and Ziskin (palm)	4.52	31.7	6.9 ps	1.4 S/m



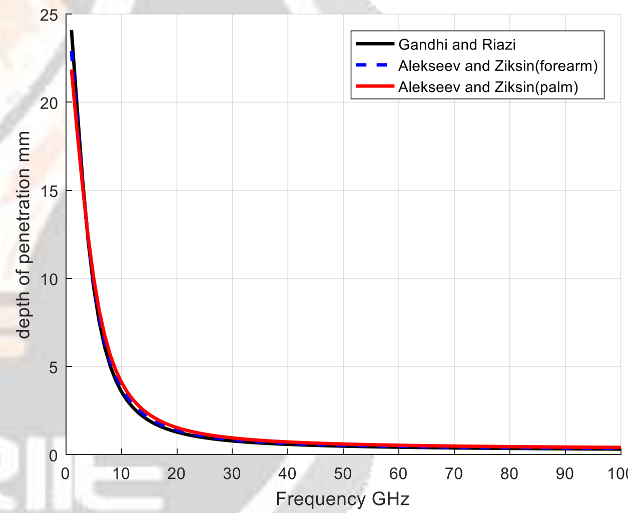


Fig. 5: Penetration depth in Skin from 100 MHz to 20 GHz and 20 GHZ to 100 GHz

We can see that the higher the frequency the more the wave fails to penetrate in depth. From 10 GHz the penetration depth decreases rapidly with increasing frequency.

2.3 Energy absorbed in biological media

Dosimetry involves at establishing the relationship between an electromagnetic field distribution in free space and the fields induced inside biological tissues or generally the human body. In other words, it is the quantification of the energy within a medium exposed to an electromagnetic field by evaluating the specific absorption rate (SAR) in the medium, which is given by the relation:

$$SAR = \frac{\sigma}{\rho}E^2 \quad (11)$$

Where

- σ is the tissue conductivity
- ρ tissue density
- E the magnitude of the electric field

For a given power density of the wave incident to a tissue, the SAR can be calculated from the relation (12) [5]

$$DAS(0) = \frac{2D(1 - R^2)}{\rho\delta} \quad (13)$$

$$DAS(x) = DAS(0)e^{-\frac{2x}{\delta}} \quad (14)$$

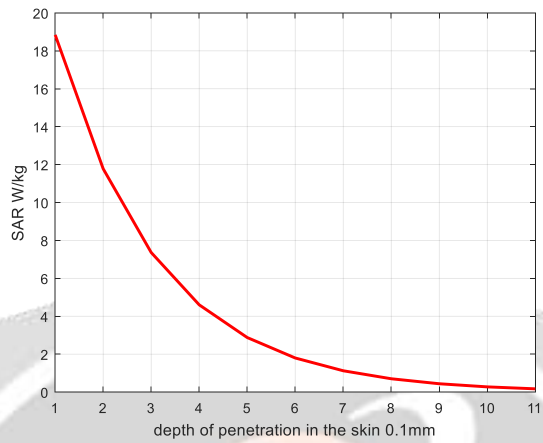


Fig. 6: SAR attenuation in the skin at 60 GHz

Figure 4 shows the attenuation of SAR in the skin at 60 GHz, it is clearly seen that very little energy is absorbed and most of it is absorbed in the epidermis (0.2 mm depth).

4. ELECTROMAGNETIC WAVES COUPLING WITH THE HUMAN BODY

Coupling is involved in interaction mechanisms between electromagnetic fields and the body of an exposed person. Three fundamental coupling mechanisms are well established: [2]

- Extremely-low-frequency electric field coupling;
- Extremely-low-frequency magnetic fields coupling;
- High-frequency (RF and microwave) electromagnetic fields coupling

For ELF fields, the wavelength is very long the temporal variation is very slow, so the external field induces a field of quasi-static nature in the human body. Exposure to these waves occurs in the near field area.

4.1 Extremely-low-frequency electric field coupling

To illustrate the ELF electric field coupling with human body, let's take two medium 1 and 2 depicted in the figure 5 [4]

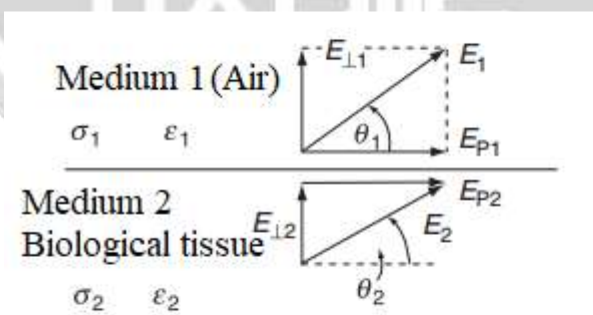


Fig. 7: Parameters at the interface between air and biological tissue

By noting E_P and $E_\perp$ respectively the parallel and perpendicular components of the E field. Following the charge conservation on the interface, we have the relation 1.19 for the ELF fields and 1.20 for the static field.

$$E_{P1} = E_{P2} \quad (15)$$

$$\sigma_1 E_{\perp 1} = \sigma_2 E_{\perp 2} \quad (16)$$

The orientations of the total E-fields in media 1 and 2 can be represented by the tangents of the angles between the total -fields and the boundary line:

$$\tan\theta_1 = \frac{E_{\perp 1}}{E_{P1}} \tag{17}$$

$$\tan\theta_2 = \frac{E_{\perp 2}}{E_{P2}} \tag{18}$$

Thus we obtain

$$\tan\theta_1 = \frac{\sigma_2}{\sigma_1}\frac{E_{\perp 1}}{E_{P1}} = \frac{\sigma_2}{\sigma_1}\frac{E_{\perp 2}}{E_{P2}} = \frac{\sigma_2}{\sigma_1}\tan\theta_1 \tag{19}$$

As the medium 1 is air which conductivity is $\sigma_1 = 10^{-13} S/m$ and let's take the typical conductivity for biological tissue $\sigma_2 = 10^{-1} S/m$, we obtain

$$\tan\theta_1 = 10^{12}\tan\theta_2 \tag{20}$$

From this relation it can be seen that even if the field in medium 2 (the inside field) is almost parallel to the boundary so that $\theta_2 \cong 0.5$; the field in the air must be perpendicular to the interface of coupling.

For Electric field ELF, we have the following equations:

$$\sigma_1 E_{\perp 1} - \sigma_2 E_{\perp 2} = -j\omega\rho_s \tag{21}$$

$$\varepsilon_1 E_{\perp 1} - \varepsilon_2 E_{\perp 2} = \rho_s \tag{22}$$

ρ_s is the surface charge density.

In the range of ELF, the relative dielectric permittivity of living tissue may be as high as 10^6

So from the equations (20) and (21), we have:

$$E_{\perp 1} = \frac{\sigma_2 + j\omega\varepsilon_2}{\sigma_1 + j\omega\varepsilon_1} E_{\perp 2} \tag{23}$$

This result shows that the external field must be almost perpendicular to the interface of the biological tissue. The electrical charges present in an organism will be attracted to its surface or pushed as the external field alternates as depicted in figure 9.

At 60 Hz $\sigma_2 = 10^{-1} S/m$, $\varepsilon_2 \approx 10^{-5} F/m$ et $\varepsilon_1 \approx 10^{-11} F/m$

$$E_{\perp 1} = -j(2.5 \times 10^7) E_{\perp 2}$$

By considering typical biological tissue

$$\frac{E_{inside}}{E_{outside}} \approx 4.10^{-8} \tag{24}$$

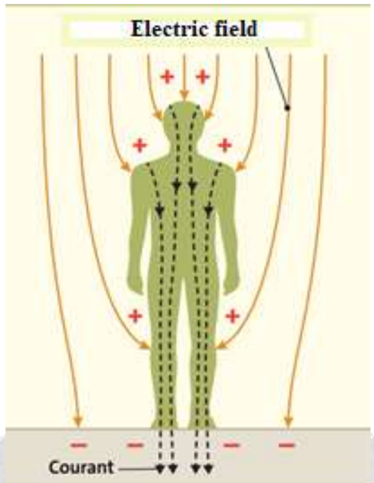


Fig. 8: Creation of current in the body due to the presence of a variable electric field [6]

4.2 Extremely-low-frequency electric field coupling

Since the permeability of biological tissues is almost equal to that of a vacuum, the human body does not disturb the external magnetic field which will therefore be equal to the field inside the body. Electric currents occur in a loop perpendicular to the direction of the magnetic field, as the human body is considered a conductor at low frequencies. [2]

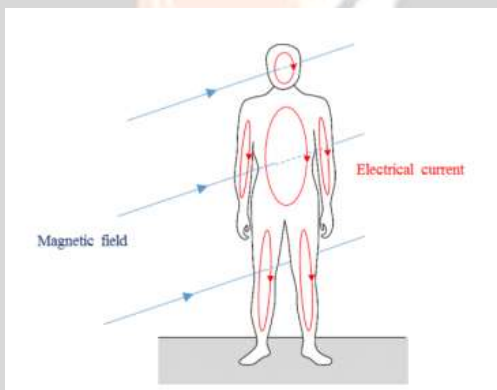


Fig. 9: Currents caused by a time-varying low-frequency magnetic field in a human body [2]

4.3 Extremely-low-frequency electric field coupling

Exposure to RF and microwave occurs in the far field where the wave can be considered as a plane wave. For a plane wave passing through medium 1 to medium 2, the reflection and transmission coefficients are given by relations 25 and 26 for the case of parallel polarization and by relations 27 and 28 for perpendicular polarization.

$$\Gamma_{\parallel} = \frac{\eta_2 \cos\theta_t - \eta_1 \cos\theta_i}{\eta_2 \cos\theta_t + \eta_1 \cos\theta_i} \qquad (25)$$

$$T_{\parallel} = \frac{2\eta_2 \cos\theta_i}{\eta_2 \cos\theta_t + \eta_1 \cos\theta_i} \qquad (26)$$

$$\Gamma_{\perp} = \frac{\eta_2 \cos\theta_i - \eta_1 \cos\theta_t}{\eta_2 \cos\theta_t + \eta_1 \cos\theta_i} \qquad (27)$$

$$T_{\perp} = \frac{2\eta_2 \cos\theta_i}{\eta_2 \cos\theta_t + \eta_1 \cos\theta_i} \quad (28)$$

Where $\theta_i$the incidence angle and η is the intrinsic impedance of the medium given by

$$\eta = \sqrt{\mu/\varepsilon} \quad (29)$$

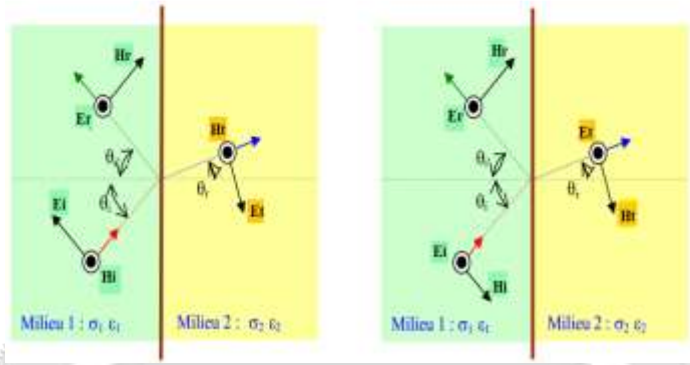


Fig. 10: parallel and perpendicular polarization to the interface [2]

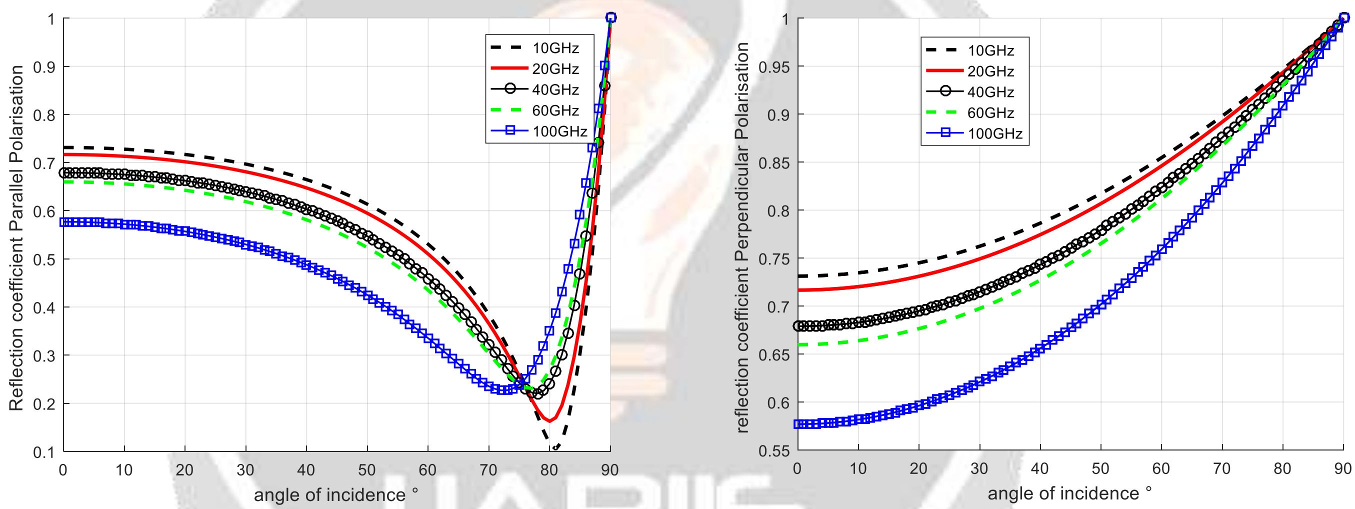


Fig -11: reflection coefficient for parallel and perpendicular polarization

The reflection coefficient depends on the incidence angle, most of the energy is absorbed at 80° and for parallel polarization and at 0° to 20° for perpendicular polarization.

5. BIOLOGICAL EFFECTS

Biological effects due to exposure to electromagnetic radiation are often referred to as being thermal or non-thermal. However, this division is imprecise. Interaction with the electromagnetic field always includes energy transfer and therewith usually a local temperature rise. However, some effects are specific for electromagnetic energy and cannot be achieved by means of conventional heat [10]

5.1 Thermal effect

The increase in temperature of a body due to the absorption of several photons can only take place in regions close to microwaves $f > 10^9\ Hz$ and for intense radiations whose intensity is greater than $1mW/cm^2$.[8]

In order to prove this, let's start with Kirchhoff's theorem stating that any material absorbs a photon of the same wavelength as it emits. In addition, the distribution of the radiation emitted by a non-black body is the same as that of a black body for the same temperature multiplied by the absorption coefficient of a non-black body for a different wavelength:

$$E_{\lambda_{non\ noir}} = \alpha_\lambda \cdot E_{\lambda_{noir}} \quad (30)$$

Where

$$\alpha_\lambda = \frac{Absorbed\ power}{incident\ power} \quad (31)$$

α_λ is the absorption coefficient (<1)

E_λ: the distribution function of the radiation capacity A

According to Planck Theorem

$$E_\lambda = \frac{2\pi \cdot h \cdot c^2}{\lambda^5} \frac{1}{e^{\frac{h \cdot c}{kT \cdot \lambda}} - 1} \quad (32)$$

The radiation capacity A of a material body is defined as the quotient of the power radiated by the body divided by its area as per relation (33)

$$A = \frac{P}{S} \quad (33)$$

This radiation capacity depends on the body temperature according to Stefan-Boltzmann law (for a black body):

$$A = \sigma T^4 \quad (34)$$

Where $\sigma = 5.672 \times 10^{-5} erg \cdot sec^{-1} \cdot cm^{-2} \cdot grad^{-4}$

Whereas, it's known that the black body emits in the infrared part, therefore the non-black bodies emit in the microwave part.

5.2 Mechanism of forced vibration of free ions.

When an electromagnetic wave penetrate in a biological tissues, it will cause movements or oscillations of the ions. To explain this phenomenon, we will consider an external electric field defined by the relation (35).This part is largely taken from [8].

$$E = E_0 \sin \omega t \quad (35)$$

This field will exert on each ion which can pass through the plasma membrane and the transmembrane proteins a periodic force (Lorentz force) given by the relation (36):

$$F_1 = E_0 z q_e \sin \omega t \quad (36)$$

This force will move the ion from its original position. Also, assuming that the ion is initially at its equilibrium position, this state will be disturbed due to its displacement due to the previous force, so it will receive a restoring force proportional to the displacement distance x.

$$F_2 = -Dx \quad (37)$$

D is the restoration constant

$$D = m_i \omega_0^2 \quad (38)$$

Where m_i the mass of an ion and the pulsation is $\omega_0 = 2\pi f_0$, f_0 is the natural frequency of oscillation of the ion defined as the frequency of a system for a spontaneous oscillation.

Finally, the moving ion undergoes a force of humidity which causes its speed to attenuate, it is defined by the following relation:

$$F_3 = -\lambda\mu \quad (39)$$

μ is the ion's speed

λ the attenuation coefficient depends on the viscosity of the media crossed by the ion (the cytoplasm, the extracellular medium and the protein channel) and its radius α (the ion is assumed to be spherical).

Thus the ion obtains an acceleration a and its equation of motion is given by the following relation:

$$m_i a = -\lambda\mu - Dx - E_0 z q_e \sin \omega t \quad (40)$$

Thus we obtain

$$m_i \frac{d^2x}{dt} + \lambda \frac{dx}{dt} + m_i \omega_0^2 x = E_0 z q_e \sin \omega t \tag{41}$$

It is a second-order linear differential equation with constant coefficient whose particular solution is of the form:

$$x_p = A \cos(\omega t + \varphi) \tag{42}$$

From (35) and (36) we obtain:

$$A = \frac{E_0 z q_e}{\sqrt{m_i^2(\omega^2 - \omega_0^2)^2 + (\lambda\omega)^2}} \tag{43}$$

And

$$\tan \varphi = \frac{m_i(\omega^2 - \omega_0^2)^2}{\lambda\omega} \tag{44}$$

Then the general solution will be the sum of this particular solution and the solution of the equation without a second member:

$$m_i \frac{d^2x}{dt} + \lambda \frac{dx}{dt} + m_i \omega_0^2 x = 0 \tag{45}$$

The solution of the equation is:

$$x_0 = C_1 e^{\xi_1 t} + C_1 e^{\xi_2 t} \tag{46}$$

With C_1 and C_2 are constants that we get from the initial conditions, ξ_1 and ξ_2 are the roots of the characteristic equation of (41).

$$m_i \xi^2 + \lambda \xi + m_i \omega_0^2 = 0 \tag{47}$$

$$\Delta = \lambda^2 - 4m_i^2\omega_0^2 \tag{48}$$

The roots are:

$$\xi_{1,2} = \frac{-\lambda \pm \sqrt{\lambda^2 - 4m_i^2\omega_0^2}}{2m_i} \tag{49}$$

Theoretically the value of Δ can be negative positive or zero, however the experimental results with different cells show that the value of ω_0 does not exceed 1 Hz, most show a value between 0.016 and 0.2 Hz. Therefore, for typical ions like Na+ we have:

$\lambda = 10^{-12}$ Kg/sec and m_i =3.8 .10^{-26} Kg thus $\lambda \gg 2mi\omega_0$ so $\Delta > 0$

The roots $\xi_{1,2}$ are therefore real and negative .The solution of (42) then tends to 0 when t tends to infinity.

Moreover, the quantity $m_i(\omega^2 - \omega_0^2)^2$ will be negligible in front of $(\lambda\omega)^2$, so in practice the particular solution will have for amplitude:

$$A = \frac{E_0 z q_e}{\lambda\omega} \tag{50}$$

We also have $m_i(\omega^2 - \omega_0^2) \ll (\lambda\omega)$ for $\omega \geq \omega_0$, so $\tan\varphi \cong 0$, $\tan\varphi \geq 0$ thus $\varphi \cong 0$ and the particular solution is written as:

$$x_p = \frac{E_0 z q_e}{\lambda\omega}\cos\omega t \tag{51}$$

The general solution of the equation (36)

$$x_p = \frac{E_0 z q_e}{\lambda\omega}\cos\omega t + C_1 e^{\xi_1 t} + C_1 e^{\xi_2 t} \tag{52}$$

For a reasonable value of $\nu_0 = \frac{\omega_0}{2\pi} = 0.1\ \text{Hz}$, we have

$$\xi_1 \cong -1.5 \cdot 10^{-14} sec^{-1} \cong 0 \tag{53}$$

$$\xi_2 \cong -2.6 \cdot 10^{13} sec^{-1} \tag{54}$$

If we consider the following initial conditions: at $t = 0$ $x_{t=0} = 0$ and $\left(\frac{dx}{dt}\right)_{t=0} = \upsilon_0$, then from (45) we obtain

$$C_1 + C_2 = -\frac{E_0 z q_e}{\lambda\omega} \tag{55}$$

$$C_1\xi_1 + C_2\xi_2 = \upsilon_0 \tag{56}$$

Thus

$$C_1 \cong -\frac{E_0 z q_e}{\lambda\omega} \tag{57}$$

$$C_1 \cong -\upsilon_0 4 \times 10^{-14} \tag{58}$$

$$C_2 e^{\xi_2 t} \cong 0 \tag{59}$$

And we obtain

$$x = \frac{E_0 z q_e}{\lambda\omega}\cos\omega t - \frac{E_0 z q_e}{\lambda\omega} \tag{60}$$

Note that the ion moves a fixed distance of $\frac{E_0 z q_e}{\lambda\omega}$ from its vibrating motion. However, this term is negligible compared to the oscillating term so the vibrational movement is described by the following equation:

$$x = \frac{E_0 z q_e}{\lambda\omega}\cos\omega t \tag{61}$$

5.3 Heat transfer model in biological tissues.

The mathematical modeling of thermal diffusion in biological tissues is based on the work of Pennes published in 1948. The Pennes equation assumes that all heat transfer between tissue and blood takes place in capillaries and that thermal conductivity, the blood perfusion rate and metabolic heat production are uniform, it takes into account the blood perfusion. In this model the variation in temperature created by the absorption of electromagnetic energy is given by the relation (62). [9]

$$\rho C_{\rho} \frac{\partial T(t)}{\partial t} = \nabla \cdot (k\nabla T) + \rho.SAR - B(T - T_b) \quad (61)$$

Where *T(t)* is the temperature of the tissue at time t, ρ of the tis is the mass density of the tissue [kg/m^3], c : is the heat capacity [J/kg °C], k: is the thermal conductivity of the tissue [J/s.m °C], B: is the blood perfusion rate,. There are still several models of heat transfer in biological tissues based on the improvement of this model, however it is still the most widely used model because of its simplicity but relatively precise.

5.3 Non-thermal effects

Non-thermal effects are effects observed on biological systems, when the amount of energy absorbed is too small to induce a rise in temperature. To explain the mechanism of wave interaction that causes these effects, one approach is to assume that an external oscillating field exerts an oscillating force on the free ions inside and outside the cells membrane that can pass through it by transmembrane proteins. This force causes a forced vibration of the free ions. When this force reaches a threshold value, the moving ions can give false information in the opening and closing control signals (mechanical or electrical) of the channels. This causes the electrochemical imbalance of the plasma in the cell which will subsequently disrupt the function of the entire cell. According to [8] a change of 30 mV in the potential of the membrane makes it possible to close or open the voltage-gated ion channels VGIC and a displacement of an ion of $\partial r = 10^{-12} m$ on S4 allows for such a change [8][12][13]. By setting F the force which acts and q the effective load on the domain S4 and assuming that:

$$q = 1.7 q_e \quad (62)$$

From the formula of membrane potential

$$F = \frac{\Delta\psi}{S} q \quad (63)$$

So we have

$$\Delta F = \frac{q}{S} \Delta\psi \quad (64)$$

Thus by taking $\Delta\psi = 30\ mV$ and $S = 10^{-8} m$ we obtain the relation (65) which is the value of the necessary force to open or close the voltage-gated ion channel.

$$\Delta F = 9.16\, 10^{-13} N \quad (65)$$

The displacement of a cation z-valence which makes it possible to open or close an ion channel is given by the following relation:

$$\partial \mathrm{r} = -\frac{2\pi\varepsilon\varepsilon_0 \partial \mathrm{F} r^3}{q.\, z q_e} \quad (66)$$

r is the distance between the oscillating ion and the effective charge of the S4 domain. This distance can be thought of as 1 nm which is the value of the force required to open or close a voltage controlled ion channel. ε_0 is the dielectric constant of vacuum and ε: the relative dielectric constant, it can have a value of 80 for media that share the same characteristics with water (cytoplasm or extracellular spaces). For ions crossing protein channels, it can have a very low value like 4. According to Coulomb's law the force exerted by an ion at one valence on the effective charge of an S4 domain is given by the following relation:

$$F = \frac{1}{4\pi\varepsilon\varepsilon_0}\frac{zq_0q_e}{r^2} \tag{67}$$

Thus we have

$$\partial F = -2\frac{1}{4\pi\varepsilon\varepsilon_0}\frac{zq_0q_e}{r^3} \tag{68}$$

So $\partial r \cong 0.8\,10^{-10}$m for $\varepsilon = 80$, $\partial r \cong 4\,10^{-12}$ m $\varepsilon = 4$ and $\partial r \cong 2\,10^{-12}$ m for a double valence cation. So we can see that a displacement of a cation of a few pico meters allows to toggle the state (open or closed) of the voltage-controlled channel port. Free ions are always in motion due to these thermal activities with greater kinetic energy than that caused by external electromagnetic fields. These movements are randomly in all possible directions for each ion, so it does not cause the ion cloud to move and therefore does not reach the switch of the state of the ion channel. Whereas the forced vibrations of ions caused by an external electromagnetic field are coherent movements of all ions together in phase. The movement due to thermal activities is negligible compared to that caused by the external field and only the latter can affect the functioning of the cells described above.

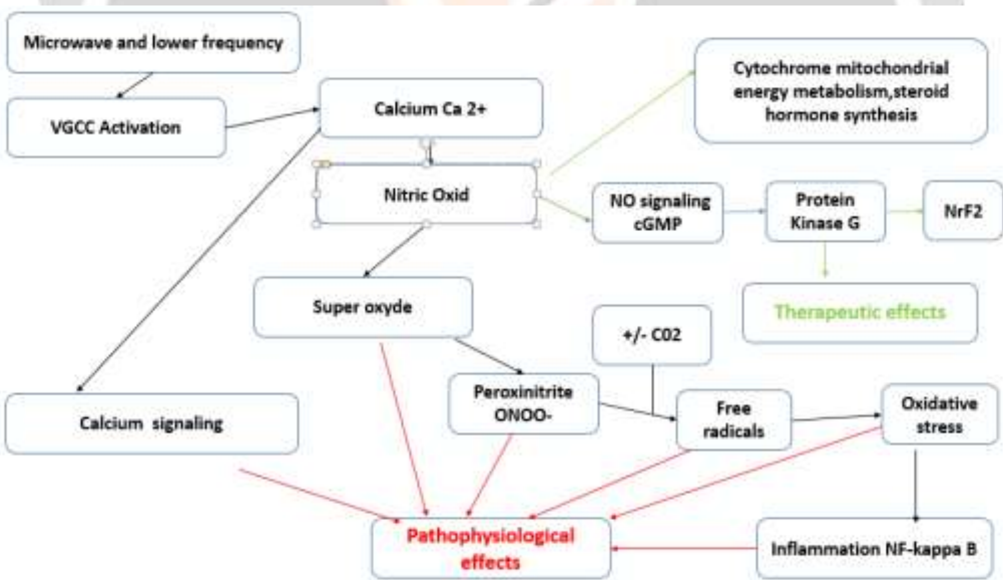


Fig -11: Various pathways of action by which electromagnetic fields can activate VGCC and lead to biological effects [14]

Figure 11 shows the possible modes of action following VGCC (Voltage-Gated Calcium Channels stimulation from electromagnetic fields.

In [13] and [14], it is reported that both extremely low frequency (including static fields) and Microwave range exposure act via VGCC activation. This stimulation leads to increased intracellular Ca^{2+}, which can act in turn to stimulate the two calcium/calmodulin-dependent nitric oxide synthases and increase nitric oxide. The increase nitric oxide can lead to both therapeutic/potentially therapeutic and pathophysiological responses:

- The nitric oxide via its main physiological way stimulates the cGMP and protein Kinase. This is buttressed by substantial example like the stimulation of bone growth via modulated electromagnetic field stimulation of osteoblasts, which appears to involve an elevation/nitric oxide/protein kinase G pathway

- Nitric oxide act in pathological response by acting as precursor of peroxynitrite, producing both oxidative stress and free radical breakdown products. For example, it seems likely that the EMF induction of single-stranded DNA breaks involves a Ca^{2+}/elevation/nitric oxide/peroxynitrite/free radical (oxidative stress) pathway.

5. CONCLUSIONS

As a conclusion, electromagnetic fields from artificial source used in the range up to 300 GHz are non-ionizing. In the static range and extremely low frequency (up to the frequency of 100 kHz), electromagnetic fields induce currents inside our body that can lead to the stimulation of excitable tissues (nervous system and muscles). Above 100 kHz, the energy absorbed by the body is proportional to the intensity of the field and it is quantified by SAR which in W/kg. The absorbed energy is then transformed into heat. The electromagnetic field absorption depends on the frequency and on their dielectric properties of the biological tissues. It is more significant in tissues with a high water content but the higher the frequency, the less the field can penetrate into the tissue. The heat increase is often modelled using Pennes' Bio-heat equation which takes into account the blood perfusion rate and metabolic heat production. The heat deposited by the electromagnetic radiation is added to that produced by the organism's metabolism. Between 100 kHz and 10 MHz the heating and stimulation can coexist. Other possible effects such as non-thermal effects are still the subject of scientific debates such as genotoxicity, the risk of cancer, effects on cell multiplication, and changes in the permeability of the blood - brain barrier, disturbances enzymatic and hormonal. We have introduced in this article the hypothesis from which the non-thermal effects may occur. It is based on the activation of the voltage-gated calcium channels VGCC by the electromagnetic fields which may lead to therapeutic or pathophysiological responses. Yet, these latter effects are not recognize by the WHO (World Health Organization) and the regulatory bodies like ICNRIP (International Commission on Non-Ionizing Radiation Protection), FCC (Federal Communications Commission) and IEEE (Institute of Electrical and Electronics Engineers) so the current exposure limits are still based on the principle to prevent from stimulation and heating. Studies on electromagnetic fields biological effects should deepen in order to be safely use technology and protect the human kind.

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