DESCRIPTION OF THE BIOLOGICAL, ELECTRICAL AND ELECTROMAGNETIC CHARACTERISTICS OF THE HUMAN BODY

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ABSTRACT

The increase of exposure of the population to electromagnetic radiation produced by base stations and a plethora of electronic user equipment for wireless communications technologies is causing global concern. As sufficiently high power electromagnetic fields can adversely affect health, exposure limits have been established by regulatory bodies like ICNIRP (International Commission on Non-Ionizing Radiation Protection), FCC (Federal Communications Commission), and IEEE (Institute of Electrical and Electronics Engineers). Fuelled by social media, the alleged effects of exposure to electromagnetic fields, while not necessarily supported by scientific facts, are rapidly spreading around the world. In order to understand the basics of the mechanisms of interactions of electromagnetic fields with the human body and the possible biological effects, it is first of all essential to know the characteristics of biological media as precisely as possible. The main objective of this publication is to describe the biological environments from three different angles, namely from a biological, electrical, and electromagnetic point of view, and detail the mathematical models that govern basic biological processes. Biological materials are complex and have different properties to those of the materials used in the domain of electricity. Each biological tissue has its own electrical properties and it differs significantly from other tissues. The biological medium is highly dispersive, at low frequency, they can be considered as a conductor even if their permittivity can be high, however at high frequency, they behave like a lossy dielectric medium. These properties make it possible to determine how the electromagnetic fields penetrate tissue and how they will interact.

Keyword: - *biological material, cell membrane, ionic conductivity, Complex permittivity, dispersion,*

1. INTRODUCTION

The human body is a very complex system, it is made up of made up of thousands of billions of cells that form tissues and organs. The body is made up of around 200 different types of cells that perform different functions. Cells of the same type join together to form tissues such as the lining of the intestine or the surface of the skin. Then, different types of tissue come together to form an organ such as the heart, liver, spleen, and stomach. First, we will describe biological cells and tissues from a biological point of view. Then in the second part, we will give the electrical models of the cell and in the third part we will focus on the electromagnetic properties of biological tissues and the empirical models that allow them to be represented.

2. BIOLOGICAL MEDIA FROM A BIOLOGICAL POINT OF VIEW

The human body is made up of different types of biological media with very different properties. These biological media can be: fluids (cerebrospinal fluid, synovia, urine) composed of water, organics and minerals, and tissue made up of a collection of cells that will make up the organs. The cell is the smallest unit capable of life autonomous and reproductive and also the vehicle for transmitting genetic information. It is the fundamental structural and functional unit of all living things.

2.1 Cell structure

A cell is made up of:

- a plasma membrane which is made up of a bilayer of phospholipids and membrane proteins.

- a cytoplasm rich in organelles
- Mitochondria, which provide energy for the cell to function
- The endoplasmic reticulum which ensures the transport and storage of materials inside the cell
- Peroxisomes, which isolate the reactions during which oxygenated water (chemical reagent dangerous for the cell) is formed and degraded.
- Ribosomes which are composed of proteins and RNA (ribonucleic acid), they are the seat of protein synthesis
- Lysosomes and vesicles: intracellular digestion
- The cytoskeleton, made up of microtubules and other filaments [1]

2.2 The cell membrane

The plasma membrane is the membrane that limits the living part of the cell and separates it from the external environment. Its thickness is approximately 75 Å. It is made up of three of the main basic elements of life, lipids, proteins and carbohydrates. These three elements cooperate to form a fluid but nonetheless sealed film which isolates the cell from the external environment and allows it to interact. [2]

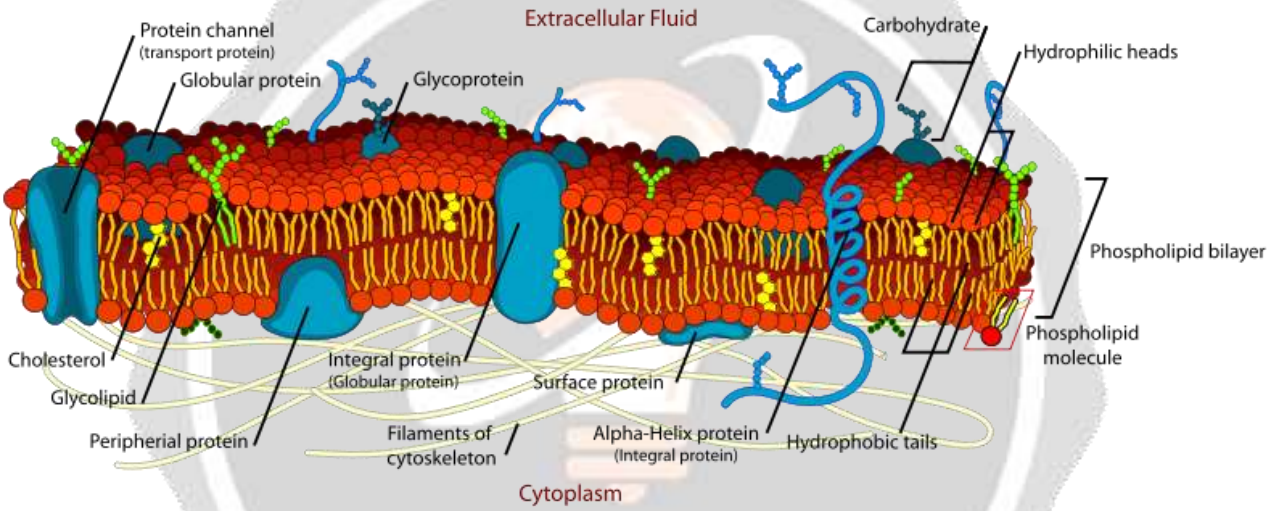

Fig -1: Cell membrane structure [3]

It mainly performs the following functions: information exchange with other cells (hormonal receptors, gap junctions), regulation of metabolism (intracellular transduction of extracellular signals), regulation of transport of ions, proteins, sugars, fats, etc.

2.3 Membrane transport and cellular exchanges

The cells selectively take from their environment different materials (nutrients, oxygen, etc.) necessary for their operation, and excrete the resulting waste there. Membrane transport is the passage of a molecule, ion or particle through the phospholipid bilayer of the plasma membrane or organelles. Membrane transport can take place:

- without membrane movements (passive or active transport if they require an energy source);
- with membrane movements (vesicular traffic)

In this article, we will focus on transport without membrane movement, particularly in passive transport of the facilitated diffusion type, this type of transport involve transmembrane proteins that facilitate the speed of passage. There are three types of protein channels in the membrane:

- Voltage-Gated Ion Channel VGIC (protein channels whose opening and closing is controlled by a potential difference across the membrane)
- Mechanically-gated Channel): channels whose opening and closing is controlled by the ion pressure present on the membrane.
- Ligand-dependent or ligand-gated ion channels: they open or close depending on the binding of a ligand to the channel

The VGIC voltage-controlled ion channels are mainly sodium Na+, calcium Ca2+, chloride Cl- and potassium K +. The state of these channels is determined by the electrostatic interaction between the membrane voltage and the

channel voltage sensors. The channels are opened or closed when the electrostatic force acting on the charges of the voltage sensors reaches a threshold value.

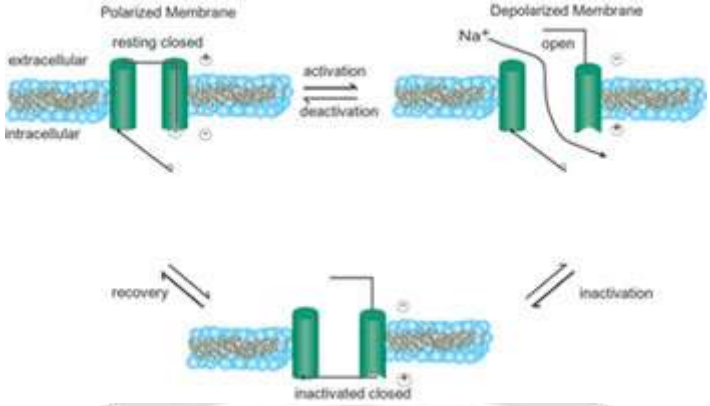

Fig -2: mechanism of VGIC [4]

In the closed rest state, the cell membrane is polarized, the extracellular part of the pore is closed while the intracellular trigger mechanism remains open. Upon activation, the membrane depolarizes, opening the extracellular part of the pore and allowing the ion to enter the cell. The refractory period occurs while the membrane is still depolarized, the trigger mechanism has closed the intracellular part of the pore, rendering the channel inactive. [1][2][3][4]

3. BIOLOGICAL MEDIA FROM THE ELECTRICAL POINT OF VIEW

Membrane potentials correspond to the differences in potential across the plasma membrane of a cell.
In both sides of the plasma membrane (inside and outside) there are mainly free ions: potassium K, sodium Na +, they have the role of:

- Control the volume of the cell by osmotic pressure
- Control the entry and exit of water
- Participate in the metabolic process and signal transduction
- Create an intense electric field between the inside and the outside of the membrane.

The difference in potential between the interior and exterior of the membrane at equilibrium is given by the Nernst equation [2]:

$$\psi_o - \psi_i = -\frac{RT}{zF} ln \frac{C_o}{C_i} \quad (1)$$

Where

- R: the ideal gas constant
- T: temperature
- F: Faraday's constant
- z: the valence of the ion

The potential difference across the plasma membrane of animal cells varies between 20 mV and 200 mV. Thus the intensity of the transmembrane electric field is of the order of 10^7 mV.
As the electric field is given by the relation (2)

$$\boldsymbol{E_m} = \frac{\Delta\psi}{S} \quad (2)$$

By taking s = 100 A ° the typical width of the membrane and $\Delta\psi$ = 100 mV, we have $E=10^7 V/m$

2.1 Equivalent cell circuit

In H. Fricke's model, the cell membrane can be compared to a capacitor C_m and the intra and extra cellular media are considered as liquid electrolytes. This model associates with each constitutive part of the cells and the external

environment an equivalent passive electrical component: the cytoplasm is described by the resistivity R_c and the ambient environment by the resistance R_e. [2][5]

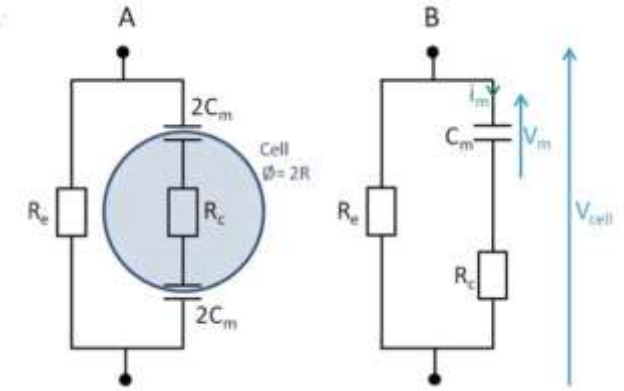

Fig -3: equivalent circuit of the cell

Kirchhoff's law can be written as follows:

$$V_{cell} = V_m + R_c C_m \frac{dV_m}{dt} \quad (3)$$

By taking an electric field of amplitude E applied to a cell of radius rc we have:

$$2r_c E = V_m + R_c C_m \frac{dV_m}{dt} \quad (4)$$

By considering that Vm is zero at the initial time and that the electric field E is constant Vm is given by 5

$$2r_c E = V_m + R_c C_m \frac{dV_m}{dt} \quad (5)$$

Where $\tau = R_c C_m$

This simple model shows a linear dependence of the transmembrane voltage with the radius of the cell.

2.1 Ionic conductivity

Ionic conductivity is a transfer of charges accompanied by the movement of a substance, producing changes in most of the electrolyte. Ionic conductivity is defined as composed of the distinct contributions of anions (negative charge) and cations (positive charge). We can thus define the current density J in (A / m²) for a simple anion-cation pair**.**

$$J = (nz_e v)_+ + (nz_e v)_- \quad (5)$$

Suppose an ion of an electrolyte carrying the charge q> 0 subjected to the action of an electric field, and with a force of friction proportional to the speed, and of opposite direction: the fundamental relation of the dynamics gives:

$$m\frac{d\vec{v}}{dt} = -h\vec{v} + q\vec{E} \quad (6)$$

The solution is

$$\vec{v} = \frac{q\vec{E}}{h}\left(1 - e^{-\frac{ht}{m}}\right) - h + q\vec{E} \qquad si\ \vec{v}(0) = \vec{0} \quad (7)$$

If we only focus on the steady state, i.e. when t → ∞, we see that the speed tends towards a limit:

$$\vec{v}_l = \frac{q\vec{E}}{h} = \frac{q\tau\vec{E}}{m} \quad (8)$$

Where μ is the mobility of the ion. The current density is then expressed by the relation 9

$$J = nqv_l = nq\mu E \quad (9)$$

Whereas the concentration is given by the relation 10

$$c = \frac{n}{Na} \quad (10)$$

And

$$q = ze \quad (11)$$

Thus

$$J = N_a cq\mu E = czN_a e\mu E = czF\mu E = cz\lambda E = \sigma E \quad (12)$$

Where

F = Na_e: Faraday's constant

λ = Fμ the molar ionic conductivity of the ion [$s.m^{-2}.mol^{-1}$]

σ: $cz\lambda$ the conductivity of the solution

And by applying Kohlrausch's law we get the relation (5) [6]

2.1 Membrane ionic conductivity

An ion channel allows an ionic species to pass in a given direction in accordance with its electrochemical gradient. Its behavior is simply modeled by resistance. The total current through the plasma membrane is given by the sum of the ionic currents and the charge and discharge current of the membrane capacity. [6]

$$I_m = I_c + I_X \quad (13)$$

Where

$$I_c = C_m \frac{\partial V_m}{\partial t} \quad (14)$$

C_m is the capacitance of the membrane, V_m the voltage across the membrane

The current i_X of X ions through this channel is proportional to its electrochemical gradient

$$i_X = \sigma_X \psi (V - V_X) \quad (15)$$

Where

- σ_X: the ionic conductivity
- V: the membrane potential

- V_X: the electrochemical potential of ion X

4. ELECTROMAGNETIC PROPERTIES OF BIOLOGICAL MEDIA

The electrical and magnetic properties of materials are a measure of their response to stimulation by external electric and magnetic fields, respectively. These are intrinsic properties of matter determined by the extent of interactions with an external electric or magnetic field at all levels of organization of matter, including structural, molecular, atomic, and electronic. Electrical permittivity and magnetic permeability are the properties used to characterize and quantify these interactions. In most biological materials, the magnetic permeability is close to that of free space (i.e. non-magnetic), which implies that there is no direct interaction with the component magnetic of low-intensity electromagnetic fields. [7]

4.1 Polarization in biological media

Electrical polarization can be defined as the disturbance induced by the electric field of the distribution of charge in a region. There are many free and bound charges in biological matter, an applied electric field will cause them to drift and move, thus inducing conduction and polarization currents. When a charge distribution is subjected to an electric field, the set of positive and negative charges separate under the action of the Coulomb force. [8]

For a set of dipoles contained in a volume V, the polarization is given by the relation (16)

$$P = \frac{\langle M \rangle}{V} \tag{16}$$

M being the macroscopic dipole moment and the symbol $\langle\rangle$ indicates the set of all dipoles and V the volume. It is the association of the contribution of the dipole moments of each molecule, divided by the volume of the material in which they are contained. For the linear approximation, the macroscopic dipole moment is proportional to the strength of the electric field.

$$P_i = \varepsilon_0 \chi_{ik} E_k \tag{17}$$

With ε_0 the permittivity of the vacuum, χ_{ik} the susceptibility of the dielectric and E_k the component of the electric field. If the dielectric is uniform and isotropic, then χ is a scalar, so (15) becomes

$$P = \varepsilon_0 \chi E \tag{18}$$

Further, according to Maxwell, matter is considered a continuous charge distribution and that the electric field inside expressed by the displacement field D is defined as the electric field corrected by polarization.

$$D = \varepsilon_0 E + P \tag{19}$$

For a uniform isotropic medium the three vectors D, E and P have the same direction and the susceptibility does not depend on the coordinates as follows:

$$D = \varepsilon_0 (1 + \chi) E = \varepsilon_0 \varepsilon_l E \tag{20}$$

ε_l is the low frequency permittivity often called dielectric constant however it can vary according to several parameters for the variable fields.

Polarization does not occur instantaneously and the associated time constant is called the relaxation time τ. The dielectric relaxation time measures the time required for the reestablishment of electrical neutrality. It can be measured by applying a unit step function as an excitation and then monitoring the relaxation process towards a new equilibrium in the time domain. Relaxation of electrons and small dipolar molecules is a relatively fast process, with

relaxation times in the pico and nanosecond range, while polarization on interfaces can give relaxation times on the order of seconds, it can be written as follows:

$$(t) = \varepsilon_0 \left[\varepsilon_h E(t) + \int_{-\infty}^{t} \Phi(t - t') E(t) dt \right] \quad (21)$$

$\Phi(t)$ is the response function of the dielectric

$$\Phi(t) = (\varepsilon_l - \varepsilon_h)[1 - \Phi(t')] \quad (21)$$

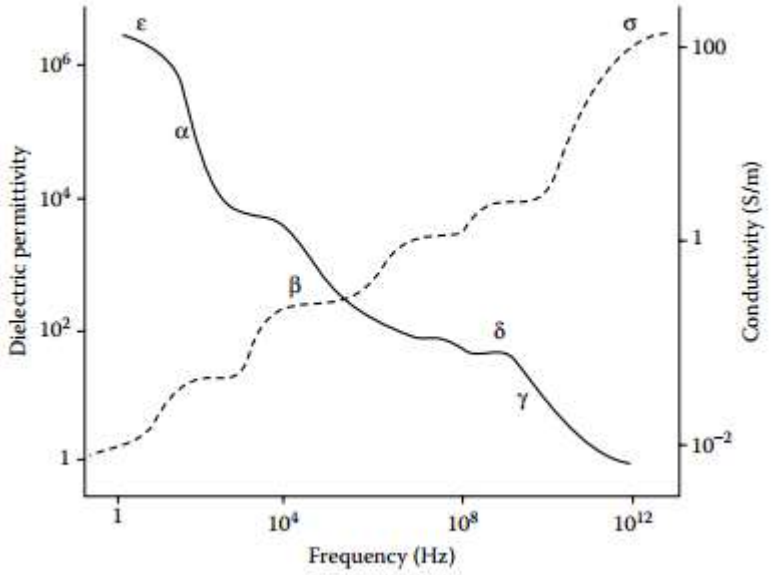

Fig -4: dielectric dispersion of a muscle-like biological tissue [9]

Biological materials exhibit very high dielectric constants, especially at low frequencies, compared to other homogeneous solids and liquids. This is because biological tissues are made up of macromolecules, cells, and other membrane-bound substances. Likewise, they exhibit high conductivities at low frequencies. Cell membranes have a relatively high capacity at low frequencies. In figure 1.04, there are four zones of dispersions: below 10 kHz, the dispersion α is associated with polarizations on the interfaces associated with electrical double layers and with surface ionic conduction effects at the membrane boundaries. The β dispersion arises from the interfacial polarization of cell membranes, which act as a barrier for the passive transport of ions between the internal and external cellular media. Referring to the equivalent circuit of the membrane in figure 4, the dispersion occurs in the range of frequencies where the reactance of the capacitance of the membrane short circuits its resistance such that the external field can enter inside the cell. . The γ dispersion: it comes from the relaxation of free water in the tissue and is found at 17 GHz. [9] [10]

4.2 Complex permittivity and conductivity

Dielectric dispersion is the change in permittivity with frequency. A dispersion will then be the transition from one level to another, where the median value between these two levels will occur at the characteristic frequency fc. For the polarization induced by the electric fields varying in time, the permittivity becomes complex and varies depending on the frequency, it is given by the relation (22):

$$\varepsilon^*(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega) \quad (22)$$

The real part $\varepsilon'(\omega)$ reflects all the losses in the medium (ohmic and dielectric). The imaginary part $\varepsilon''(\omega)$ reflects the polarization of the material which corresponds to an energy storage in the form of an electric field.

Considering a sinusoidal electric field:

$$E^*(t) = E_0 e^{j\omega t} \quad (23)$$

Where E_0 is its amplitude, $\omega = 2\pi f$ the pulsation, f the frequency in Hz

As the movement of the microscopic particles cannot follow the variation of the electric field, the polarization and the displacement field will no longer be in phase as in the static case. The displacement field can then be written in the form:

$$D^*(t) = D_0 e^{j(\omega t - \delta(\omega))} \quad (24)$$

$\delta(\omega)$ is the phase shift with the electric field as a function of the frequency.

By comparison of the relations 23 and 24, we see that by introducing complex permittivity, we can write the following relation:

$$\varepsilon^*(\omega) = \frac{D_0}{\varepsilon_0 E_0} e^{-j\delta(\omega)} \quad (25)$$

Generally when the applied field is a linear combination of several harmonic components, the amplitudes D_0 depend on the frequency. We have:

$$D^*(\omega) = \varepsilon_0 \varepsilon^*(\omega) E^*(\omega) \quad (26)$$

Using Euler's formula to transform the components of the exponential into a function of sine and cosine, we obtain the relation 22 with

$$\varepsilon'(\omega) = \frac{D_0(\omega)}{\varepsilon_0 E_0(\omega)} \cos(\delta(\omega)) \quad (27)$$

$$\varepsilon''(\omega) = \frac{D_0(\omega)}{\varepsilon_0 E_0(\omega)} \sin(\delta(\omega)) \quad (28)$$

$$D_0(\omega) = \varepsilon_0 E_0(\omega) \sqrt{\varepsilon'(\omega)^2 + \varepsilon''(\omega)^2} \quad (29)$$

$$\tan\delta(\omega) = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} \quad (30)$$

There are empirical models to approximate the frequency variations of the electrical properties of biological media.[8]

4.3 Debye model

In this model [8], the complex permittivity is expressed as:

$$\varepsilon'(\omega) = \frac{\varepsilon_l - \varepsilon_h}{1 + j(\omega\tau)^2} + \varepsilon_h \tag{31}$$

$$\varepsilon''(\omega) = \frac{\varepsilon_l - \varepsilon_h(\omega\tau)}{1 + j(\omega\tau)^2} + \varepsilon_h \tag{32}$$

$$\tan\delta(\omega) = \frac{\varepsilon_l - \varepsilon_h(\omega\tau)}{\varepsilon_l + \varepsilon_h(\omega\tau)^2} \tag{33}$$

Debye's model assumes that the relaxation function follows an exponential decay described by the relation:

$$\Phi(t) = e^{-\frac{t}{\tau}} \tag{34}$$

By differentiating 34, we obtain

$$\frac{d\Phi(t)}{dt} = -\frac{1}{\tau}\Phi(t) \tag{35}$$

By differentiating relation 21 and using 35, we have

$$\tau\frac{dE(t)}{dt} = \varepsilon_h\tau\frac{dE(t)}{dt} + \tau\Phi(0)E(t) - \int_{-\infty}^{\tau} E(u)\,\Phi(t-u)\,du \tag{36}$$

By adding 21 and 36 we obtain

$$\tau\frac{d}{dt}(D - \varepsilon_h E) + (D - \varepsilon_h E) = \tau\Phi(0)E \tag{37}$$

To determine the constant Φ (0), we will consider the case at equilibrium on a constant field, that is to say

$$\tau\frac{d}{dt}(D - \varepsilon_h E) = 0 \tag{38}$$

And

$$D = \varepsilon_l E \tag{39}$$

So from (37) we have:

$$\tau\Phi(0) = \varepsilon_l - \varepsilon_h \tag{40}$$

So (37) becomes:

$$\tau\frac{d}{dt}(D - \varepsilon_h E) + (D - \varepsilon_h E) = (\varepsilon_l - \varepsilon_h)E \tag{41}$$

This equation therefore represents the differential equation which links E and D for the relaxation function given by (41) and (35)

$$\Phi(t) = -\frac{(\varepsilon_l - \varepsilon_h)}{\tau} e^{-\frac{t}{\tau}} \quad (42)$$

By introducing (42) in (21) we obtain

$$\varepsilon(\omega) - \varepsilon_h = (\varepsilon_l - \varepsilon_h)\frac{1}{\tau}\int_0^{+\infty} e^{i\omega x - x/\tau} dx \quad (43)$$

By integrating (43) we have

$$\varepsilon(\omega) - \varepsilon_h = \frac{(\varepsilon_l - \varepsilon_h)}{1 - i\omega\tau} \quad (44)$$

By separating the real and imaginary part we get Debye's equation. Note that the exponential relaxation function i.e. Debye's model can only be obtained by considering that the particles are independent of each other. It is a simple model giving a good representation of the frequency behavior of the conductivity and the permittivity of biological media, but it does not represent the physical phenomena at the origin of this behavior. This is the basic model for the representation of relaxation phenomena.

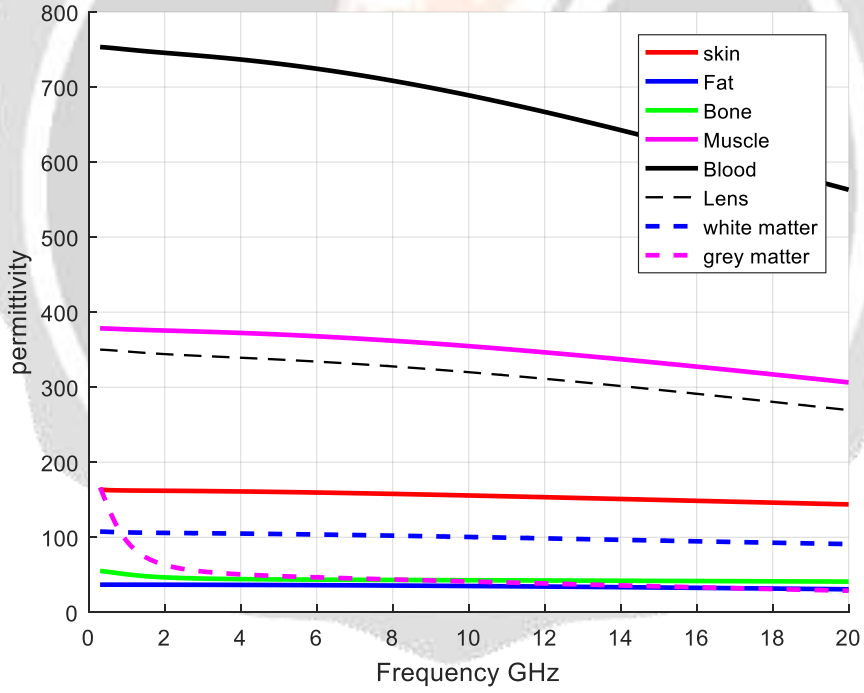

Fig -4: Head tissues permittivity 100 MHz to 20 GHz

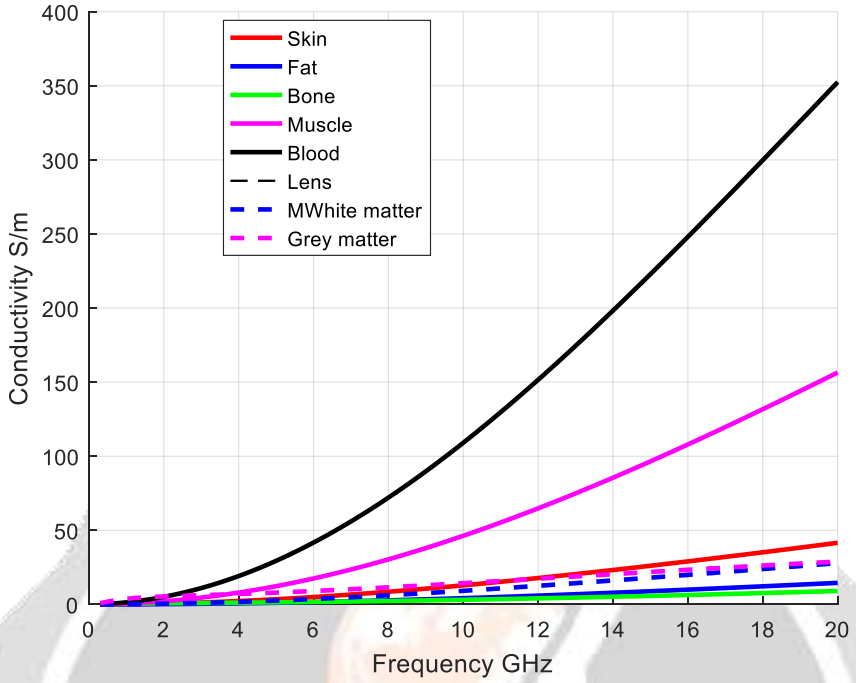

Fig -5: Head tissues conductivity 100 MHz to 20 GHz

Table 1: Three-term Debye model parameter of head tissues [11] [12]

Tissue	ε_h	$\Delta\varepsilon_1$	$\Delta\varepsilon_2$	$\Delta\varepsilon_3$	$\tau_1[ps]$	$\tau_2[ps]$	$\tau_3[ps]$
skin	4.136	32.51	2.499	125.6	7.248	527.2	1.380
fat	2.994	2.467	6.066	31.39	3.970	7904	9.739
bone	3.532	4.992	12.47	34.85	5.811	133.5	1.172
Blood	5.939	46.72	8.064	693.1	7.203	125.2	4.387
muscle	5.896	45.70	2.956	324.1	6.474	139.0	3.443
Lens	5.415	32.56	8.388	304.1	6.719	106.3	3.909
White matter	5.338	30.04	2.090	70.50	7.181	225.7	1.156
Grey matter	5.380	42.16	2.754	137.1	7.187	224.6	1.399

4.3 Cole-Cole model

This model introduces an additional parameter α characteristic of the frequency dispersion. This model is defined by the following relation [8]:

$$\varepsilon^*(\omega) = \varepsilon_h + \frac{(\varepsilon_l - \varepsilon_h)}{1 + (j\omega\tau)^{1-\alpha}} \tag{45}$$

The Cole-Cole model uses the following distribution function:

$$\Phi\left(\frac{t}{\tau}\right) = \frac{1}{2\pi}\frac{\sin\alpha\pi}{\cos h[(1-\alpha)ln(t/\tau)] - \cos(\alpha\pi)} \tag{46}$$

Using this relaxation distribution function into equation (21) and following the same processes as above, we obtain:

$$\varepsilon'(\omega) = \varepsilon_h + \frac{(\varepsilon_l - \varepsilon_h)[1 - (\omega\tau)^{1-\alpha}\sin(\alpha\pi/2)]}{1 + (j\omega\tau)^{1-\alpha} + 2(\omega\tau)^{1-\alpha}sin(\alpha\pi/2)} \tag{47}$$

$$\varepsilon''(\omega) = \varepsilon_h + \frac{(\varepsilon_l - \varepsilon_h)[(\omega\tau)^{1-\alpha}\cos(\alpha\pi/2)]}{1 + (\omega\tau)^{2(1-\alpha)} + 2(\omega\tau)^{1-\alpha}sin(\alpha\pi/2)} \tag{48}$$

The Cole-Cole model is the most used model because it allows a better representation of the permittivity compared to the measured values than the Debye model. The distribution parameter α varies from 0.3 to 0.5 in most biological media, however in millimeter bands it can take lower values. [13]

4.4 Davidson-Cole model

Another model was presented by Davidson and Cole in 1956 to improve Debye's model by introducing a parameter β which is used as an exponent in the denominator [8]:

$$\varepsilon(\omega) = \varepsilon_h = \frac{(\varepsilon_l - \varepsilon_h)}{(1 - i\omega\tau)^{\beta}} \tag{49}$$

The Davidson-Cole model uses the following relaxation distribution function:

$$\Phi\left(\frac{t}{\tau}\right) = \frac{1}{\pi}\left(\frac{t}{\tau - t}\right)^{\beta}\sin(\pi\beta) \tag{50}$$

We proceed in the same way as before and by separating the real and imaginary part we obtain:

$$\varepsilon' = \varepsilon_h + (\varepsilon_l - \varepsilon_h)\cos(\beta\phi)(\cos(\phi))^{\beta} \tag{51}$$

$$\varepsilon'' = (\varepsilon_l - \varepsilon_h)\sin(\beta\phi)(\cos(\phi))^{\beta} \tag{52}$$

Where

$$\phi = \arctan(\omega\tau) \tag{53}$$

4.5 Havriliak-Negami model

This model unites the Cole-Cole and Davidson-Cole models [8], the permittivity is given by the following relation:

$$\varepsilon^*(\omega) = \varepsilon_h + \frac{(\varepsilon_l - \varepsilon_h)}{[(1-(i\omega\tau)^{1-\alpha})]^{\beta}} \quad (54)$$

This model uses the following relaxation distribution function:

$$\Phi\left(\frac{t}{\tau}\right) = \frac{1}{\pi}\frac{(t/\tau)^{\beta(1-\alpha)}\sin(\pi\beta)}{(t/\tau)^{2(1-\alpha)}\cos\left((\pi(1-\alpha)+1)\right)^{\beta/2}} \quad (55)$$

By proceeding as we did in all the models previously and by separating the real and imaginary part we have

$$\varepsilon' = \varepsilon_h + \frac{(\varepsilon_l - \varepsilon_h)\cos(\beta\phi)}{1 + 2(\omega\tau)^{1-\alpha}\sin\left(\frac{\alpha\pi}{2}\right) + (\omega\tau)^{\frac{2(1-\alpha)\beta}{2}}} \quad (56)$$

$$\varepsilon'' = \varepsilon_h + \frac{(\varepsilon_l - \varepsilon_h)\sin(\beta\phi)}{1 + 2(\omega\tau)^{1-\alpha}\sin\left(\frac{\alpha\pi}{2}\right) + (\omega\tau)^{\frac{2(1-\alpha)\beta}{2}}} \quad (57)$$

$$\varepsilon'' = \varepsilon_h + \frac{(\varepsilon_l - \varepsilon_h)\sin(\beta\phi)}{1 + 2(\omega\tau)^{1-\alpha}\sin\left(\frac{\alpha\pi}{2}\right) + (\omega\tau)^{\frac{2(1-\alpha)\beta}{2}}} \quad (58)$$

$$\phi = \arctan\left\{\frac{(\omega\tau)^{(1-\alpha)}\cos(\alpha\pi/2)}{1 + (\omega\tau)^{(1-\alpha)}\sin(\alpha\pi/2)}\right\} \quad (59)$$

4. CONCLUSIONS

On a macroscopic scale, biological tissues can be considered homogeneous even if their structures and composition are complex; they are made up of free electrons and ions which can under the effect of an external electric field. The biological medium is a dispersive medium, it is noted that the permittivity decrease and conductivities increase when the frequency is increased. The permittivity of are relatively large compared to conventional materials especially in the low frequency part so they are considered as conductors in low frequencies and lossy dielectric medium in high frequencies. Each biological tissue has its own electrical properties and there are significant differences between them. The properties of the biological media we have described in this article will serve to create a more accurate model of the human body or organ / tissue and will be used to help us understand how electromagnetic waves interact with living things.

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