Open Journal of Applied Sciences, 2022, 12, 2096-2123
https://www.scirp.org/journal/ojapps
ISSN Online: 2165-3925
ISSN Print: 2165-3917

Analysis, Sources and Study of the Biological Consequences of Electromagnetic Pollution

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How to cite this paper: Nzao, A.B.S. (2022) Analysis, Sources and Study of the Biological Consequences of Electromagnetic Pollution. *Open Journal of Applied Sciences*, **12**, 2096-2123.
https://doi.org/10.4236/ojapps.2022.1212145

Received: October 14, 2022
Accepted: December 26, 2022
Published: December 29, 2022

Abstract

The actions and health effects of electromagnetic fields in the radio frequency (RF) domains, referred to as radio frequencies and HV transmission networks have been studied for several decades. Following the appearance of questions and debates within the population, the actions and potential effects of radiofrequency and HV transport networks on health, in connection with the development of new wireless technologies, are generating a certain revival of interest. Thus, the increasing exposure to electromagnetic fields and the concerns of the public have led health organizations to undertake large-scale research programs to respond to the concerns expressed. These research programs have contributed to significantly increasing the number of studies on the actions and effects of electromagnetic pollution as well as their consequences on living beings. The objective of our research is focused on the analysis, sources, and study of the biological consequences of electromagnetic pollution. To do this, we have used physical laws and theorems, in particular Maxwell-Ampère, Maxwell-Gauss, Maxwell-Faraday, and Ohm's law, to model the interactions between electromagnetic fields and living matter. In this article we have chosen the approach based on the electrical model of human biological tissue, taking into account on the one hand the physical phenomena of the propagation of an electromagnetic microwave plane wave in the range from 0 to 300GHz and on the other hand, the experimental values to simulate the relaxations α, β and γ and the impedance of the biological tissue faced with the variation of the frequency of propagation of the electromagnetic waves to identify the biological consequences relating thereto. The results obtained in the literature show the linear dependence of bio-impedance on frequency, these observations suggest that the tissue can be physiologically stressed at high frequencies. This can cause biological consequences for humans. The 2D simulation based on the proposed model has been developed as well as the verification of the consistency of the different mathematical models, by comparing the fractal dimensions of the results of the program with those of the figures obtained experimentally.

Keywords

Sources, Electromagnetic Pollution, Human Biological Tissue, Consequences, Electrical Model, Relaxation, Maxwell's Equations

1. Introduction

The biological and environmental effects of electromagnetic fields are the effects on living organisms of electromagnetic fields. Their intensity is assumed to depend essentially on the level of the electromagnetic field, the frequency, and the duration of exposure, or even the type of modulation [1].

This subject is the subject of controversy, in particular, concerning the level of risk for health and the environment during chronic exposure to electromagnetic fields [2], the World Health Organization recognizes the possibly carcinogenic character of static-extremely low-frequency electromagnetic fields in the light of a compilation of epidemiological data concerning childhood leukemia, but asks for scientific confirmations for more recent technologies [3].

According to several studies, this is likely to be the fastest-growing anthropogenic environmental exposure since the mid-20th century, and levels will rise again as technologies such as the Internet of Things with the launch of the 5G will add multiple dangerous additional RF transmitters to the environment [4] [5] [6].

Although electricity has been used for a long time, it is only very recently that attention has been paid to its side effects. Indeed, the impact on the health of exposure to extremely low-frequency electric and magnetic fields, mainly 50/60 hertz (Hz), has been studied mainly since the 1970s. The importance of public health of certain potential effects has generated a great deal of research and increasingly compelled governments to take an interest in them. The use of devices and technologies that use electromagnetic fields (EMF) to transmit information is growing steadily. In particular, cell phone use is increasingly common, and people do not take into account the imminent dangers it can bring. According to the International Telecommunications Union (ITU, 2019) and the Canadian Wireless Telecommunications Association (ACTS, 2019), there were already more than 6 billion subscriptions to cell phone services worldwide, and 75% of Canadian households had access to a wireless phone in 2019; this percentage representing more than 26 million subscriptions.

The actions and health effects of electromagnetic fields in the radio frequency (RF) domains, referred to as radio frequencies and HV transmission networks have been studied for several decades. Following the appearance of questions and debates within the population, the actions and potential effects of radiofrequency and HV transport networks on health, in connection with the development of new wireless technologies, are generating a certain revival of interest. Thus, the increasing exposures to radio frequencies and electromagnetic fields and public concerns have led health organizations to undertake major research programs to address the concerns expressed (World Health Organization [WHO], 2019). These research programs have contributed to significantly increasing the number of studies on the actions and effects of electromagnetic pollution.

According to [7], the results of the study by Liorni *et al.*, 2015a and 2015b, highlight a possible overcoming of the basic restrictions in the tissues of the central nervous system in the fetus, when the mother is exposed to high stock value. The results of dosimetric studies highlight a possible exceeding of the basic restrictions in the fetus in certain scenarios when the mother is exposed to a magnetic field at 50 Hz [7].

According to Anses [8], the studies carried out on cell membranes are too few and too heterogeneous to conclude the existence or not of a biological effect. However, work on artificial membranes in frequency bands between 52 and 78 GHz highlights, both structural and functional modifications.

According to [9], several studies have analyzed the potential effects of radiofrequency on the brain and nervous system in laboratory animals. These studies provided evidence indicating the possibility of measurable biological effects. Several other potential effects of radiofrequency have been the subject of cellular and animal studies, especially effects on the nervous system [8] [9], the endocrine system, the auditory system, the cardiovascular system, and the ocular system; immunological and hematological effects; effects on the blood-brain barrier.

According to the INRS [10], electromagnetic fields can have consequences on the health of exposed employees. Their effects on the body can be direct: overheating of biological tissues, stimulation of the nervous system, visual disturbances, etc. They can be indirect, causing injuries or aggravating a dangerous work situation. Based on several epidemiological studies highlighting an increased risk of leukemia in children living near high voltage lines [9] [10], very low-frequency electromagnetic fields (below 100 kHz) have been classified as carcinogenic for man. People subjected to a variable magnetic field (around a frequency of 20 Hz and above an intensity threshold of 2 to 3 mT) sometimes experience visual disturbances, characterized by the perception of luminous spots called magnetophosphenes. At an electrical network frequency of 50 Hz, these disorders can appear from exposure of the head to an external magnetic induction of 4 to 6 mT [10].

According to Rakotomananjara D.P and Randriamitantsoa P.A [11], artificial source electromagnetic fields used in the range of up to 300 GHz are non-ionizing. In the static and very low-frequency range (up to the frequency of 100 kHz), electromagnetic fields induce currents inside our body which 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 field strength and it is quantified by SAR which is in W/kg. The absorbed energy is then transformed into heat.

According to Rakotomananjara D. P and According to EPRS (European Parliamentary Research Service, 2022) [12], since 5G uses a very high level of pulses, the underlying idea is to use higher frequencies that will allow these levels. Of equally high pulses, to carry very large amounts of information per second, studies show that pulsed EMFs are, in most cases, biologically active and therefore more dangerous than non-pulsed EMFs. Therefore, while 5G may have low power, the abnormally constant pulsed radiation it produces may have an impact. Along with mode and duration of exposure, signal characteristics of 5G, such as pulsing, appear to increase biological and health risks, including DNA damage, which is believed to cause cancer. DNA damage is also associated with reduced fertility and neurodegenerative diseases. A 2018 study [12] containing more recent peer-reviewed papers on the biological and health effects of radiofrequency electromagnetic fields, including 5G, also reviews available data on the effects of millimeter waves. This study asserts that data are gradually accumulating on the biological properties of radiofrequency electromagnetic fields [12] and that although in some cases they are still tentative or controversial, they demonstrate the existence of multi-level interactions between the High-frequency EMF and biological systems, and the possibility of oncological and non-oncological effects (mainly metabolic, neurological, microbiological and reproductive system effects). She also points out that the growing scale and density of wireless devices and antennas are of particular concern. However, despite the reduced number of studies on the biological effects of 5G communication systems, an international action plan for the development of 5G networks has been launched and will lead to an increase in available devices and the density of small cells, and will require the use of millimeter waves. However, there is information indicating that millimeter waves can increase skin temperature, and promote cell proliferation and inflammatory and metabolic processes. According to this analysis, further independent research is needed to investigate the health effects of radiofrequency electromagnetic fields in general, and millimeter waves in particular [12], the higher frequency radiation from 5G, coupled with the already existing complex mix of low-frequency radiation, would have negative impacts on public health, physical and mental.

According to the work of Morgane Dos Santos [13], electromagnetic pollution by ionizing radiation is known to induce critical damage within biological matter and especially within DNA. Among these damages, DNA double-strand breaks (DSBs) are considered to be the main culprits of the lethal effects of radiation.

Furthermore, the results obtained in the work [14] demonstrate that microwave electromagnetic waves can lead to an increase in the electrical potential of biological tissues. Despite this potential is a decreasing function of the depth of penetration but, can lead to proven biological consequences. The interactions of electromagnetic waves with the human body are complex and depend on several factors related to the characteristics of the incident wave, in particular its frequency, its intensity, the polarization of the tissue encountered, the geometry of the tissue, and its electromagnetic properties [14]. That is the dielectric permittivity, conductivity, and type of coupling between the field and the exposed body. A biological system irradiated by an electromagnetic wave is traversed by induced currents of non-negligible density; the water molecules present in the biological tissues exposed to the electromagnetic field will begin to oscillate at the frequency of the incident wave, thus creating internal friction responsible for the heating of the irradiated tissues. This heating will be all the more important as the tissues are rich in water.

According to A.B.S (2022) [15], the temperature in biological tissue is a linear function of the duration of exposure to microwave electromagnetic waves.

The objective of our research is centered on the analysis, the sources, and the study of the biological consequences of electromagnetic pollution. To this end, several methods exist in the past literature to achieve this objective, in this article we have developed an algorithm based on the electrical model of human biological tissue having the advantages of taking into account, on the one hand, the physical phenomena of propagation of a plane microwave electromagnetic wave in the range of 0 to 300 GHz based on physical laws and theorems including Maxwell-Ampère, Max-well-Gauss, Maxwell-Faraday, and Ohm's law and others, on the other hand, the experimental values to simulate the α, β and γ relaxations and the impedance of the biological tissue faced with the variation of the frequency of propagation of the electromagnetic waves to identify the related biological consequences.

This article discusses electromagnetic fields in the frequency spectrum from 0 to 300 GHz (from static fields to radio frequencies); pollution due to ionizing radiation and light pollution is not dealt with there.

The organizational structure of this article focuses on the following aspects:

2. Development

2.1. Concepts and Definitions

Electromagnetic Interference

Electromagnetic phenomena are likely to cause the malfunctioning of a device or system or adversely affect living or inert matter. An electromagnetic disturbance can be noise, an unwanted signal, or a change in the propagation medium itself [16].

Electromagnetic Pollution

Most electrical and electronic equipment generates perceptible electromagnetic fields in its environment; all of these fields create real pollution, which sometimes disturbs the operation of other equipment. Thus, it is forbidden to use a mobile phone in an airplane because it emits an electromagnetic field to which the radio-electric piloting assistance systems (navigation, take-off/landing) risk being sensitive [17].

The Electromagnetic Compatibility

It designates the compatibility between co-located voluntary transmitters and receivers. It also refers to [18]:

- The techniques for obtaining the electronic compatibility of a device or installation with its environment (design and manufacturing rules);
- The techniques making it possible to verify the reality of this compatibility (numerical simulation, or via tests, standardized or not).

Emission/Susceptibility

Since compatibility must be ensured in both directions, we are led to define two types of phenomena [19]:

- Emissions (term chosen by aerospace or similar standards) or disturbances (equivalent in industrial standards) designate signals (voluntary or not) whose propagation is likely to harm the proper functioning of objects or the health of living beings located in the vicinity.
- Susceptibility designates a behavior of a device, in response to an external constraint (voluntary or not, natural or artificial), deemed incompatible with normal use. Susceptibility is also called immunity.

EMC Phenomenology

The "source/coupling/victim" model: This aspect has been developed in some work as shown in **Figure 1** below, whether it is emission or susceptibility (it is only a matter of direction), the phenomenon does not occur (or is annoying) only if there is, simultaneously [20]:

- A "source" (of a parasitic signal);
- A "victim" (vulnerable to the parasitic signal);
- And a coupling between the two.

When at least one of these elements is absent (and not necessarily the coupling, too often the only one taken into consideration), the EMC is restored. The configuration of the "source/coupling/victim" model depends on the scale at which it is viewed [21]:

- A source can be broken down into another source and a coupling: for example, the radio emission of a microprocessor is the result of the switching of logic cells (source), the metallizations of the chip as well as the tracks of the package or the printed circuit serving as an antenna to transform the temporal current transients in each cell into an electromagnetic field described by a frequency "colored fog".
- A victim can also undergo this type of decomposition, but its susceptibility criterion also varies depending on whether one "looks" at the component or the system: for example, for the same Ethernet network, one can focus.
- On the disturbance of the logic level or of the diagram of the eye (associated with the electronic component) corrupting a bit.

Figure 1. EMC problem decomposition [20].

- On the risk that the redundancies associated with the coding of the frame do not make it possible to reconstitute it.
- On the acceptability or otherwise of the reduction in bandwidth caused by the retransmission of disturbed frames.

2.2. Classifications of Electromagnetic Disturbances

Classification by Conduction and Radiation

Couplings are classified into two categories as shown in **Figure 2** below [22] [23] [24]:

- Coupling by radiation: electric field, magnetic field, electromagnetic field;
- Coupling by conduction: transmission of the signal by a conductor (any conductor, and not necessarily a piece of wire intended to conduct the electric current: an air conditioning pipe does the job perfectly).

Classification by Frequency

- *f*< 9 kHz [24]:
- These are mainly differential mode disturbances (power supply current harmonics, voltage fluctuations due to load variations, etc.).
- The magnetic and electric fields of power equipment are also to be considered in certain cases (sources: transformer, high voltage line, motor; victims: hall effect sensors, cathode ray tubes).
- 9 kHz < *f*< 300 MHz [24]:
- Disturbances conveyed mainly in common mode but may have a differential mode source.
- The radiation in this frequency band is very often carried by the cables which act as an antenna (more or less efficient depending on the length and the layout).
- We generally find broadband noises coming from the fast switching of the energy converters.
- *f*> 300 MHz [24]:
- Common mode disturbances.
- The higher the frequency, the more the disturbance will be visible only at a specific angle.
- These disturbances are essentially due to the internal clocks of the equipment, to the harmonics of these clocks, or to the radio transmitter.

Classification by Duration

We distinguish [25]:

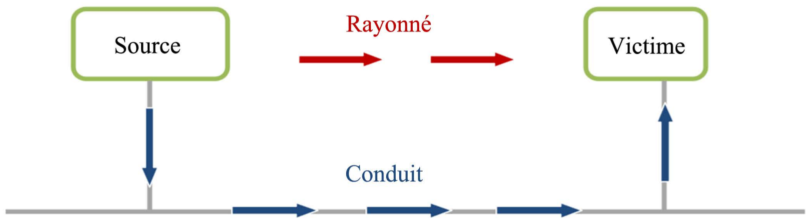

Figure 2. Coupling by radiation and conduction.

Permanent disturbances.

These are the disturbances mainly coming from:

- Radio transmitter (by direct radiation or by induction on the cables);
- The magnetic field generated by the supply lines;
- Supply voltage distortion (harmonics, DC ripple, etc.).

In general, in the regulations, the immunity of the apparatus must be sufficient to avoid a degradation of function beyond the specification during exposure to this type of disturbance.

Transient disturbances.

These are disturbances mainly originating from:

- Electrostatic discharges;
- Lightning waves;
- Electrical switching in the energy network;
- Voltage dips.

Classification by Type of Coupling

We call coupling the process by which the energy of the disruptor reaches the victim. Whenever we speak of current, voltage, or field, we should not forget that these are time-varying electrical quantities [22] [23] [24] the coupling by common impedance, capacitive coupling, inductive coupling, coupling by the electric field, coupling by magnetic field and coupling by the electromagnetic field.

Classification by Modes of Propagation

We hear very often about the two modes of propagation: the differential mode and the common mode. One could have included these two definitions in the modes of couplings, but the importance of these two terms, in particular the common mode, deserves that one defines them with precision [22] [23] [24].

2.3. Study and Analysis of Sources of Electromagnetic Pollution

It is a question of studying and analyzing the sources of electromagnetic pollution below:

Natural Sources

The terrestrial electric and magnetic fields are continuous fields generated by the electric charges present in the atmosphere (electric field) or by the magmatic currents, the solar and atmospheric activity (magnetic field). These fields are around 100 to 150 V/m for the atmospheric electric field (it can reach 20 kV/m under a storm), and around 40 μT for the magnetic field. To these are added natural alternating fields of very low value: 1 to 50 Hz, 0.013 to 0.017 μT with peaks at 0.5 μT during magnetic storms (frequency fields greater than 100 kHz) [25].

- Solar and stellar radiation produces electromagnetic waves, which are very weak compared to artificial radiation: approximately 10 pW/Cm^2.
- Living cells generate electric and magnetic fields that are usually very weak: voltage levels of 10 to 100 mV are observed, 0.1 pT on the surface of the body and in the brain, 50 pT in the heart 5. However, specialized cells and organs

exist in certain species allowing them to produce more powerful electric fields; for example, the black torpedo (Torpedo nobility) can produce electric shocks of 60 to 230 volts and exceed 30 amps.

- The difference in electrostatic charges is also among the natural sources. Electrostatic discharges (including lightning) are the consequences of these differences in electrostatic charge.

Artificial Sources

Artificial sources with static field (DC). Static field sources are typically [25]:

- Magnets (found in any microphone, loudspeaker, etc.);
- Certain medical devices such as MRIs, means of diathermy and radiofrequency ablation, etc.);
- Certain railway lines supplied with direct current, for example at 1500 v dc (France) or 3000 v DC (Belgium, Poland, etc.).

High voltage lines and electrical appliances. The frequency of electromagnetic fields emitted by high voltage (HT) and very high voltage (THT, up to 400,000 volts) lines is qualified as extremely low frequency (EBF/ELF) (50 Hz).

Near a very high voltage line, the electric field can reach 10 kV/m, and the magnetic field has several microteslas. This intensity is reduced as the distance increases, from 100 meters the magnetic field created by the lines is of the order of the average level of very low-frequency electromagnetic fields emitted by electrical appliances and electrical circuit dwellings. Also, transformers and motors generate magnetic fields that are all the more important as they are powerful.

Artificial sources in the radio frequency domain (9 kHz to 3000 GHz). The main current sources of electromagnetic disturbance are [24] [25]:

- Industrial, scientific, and medical devices;
- Certain sterilization and electricity production devices;
- Wireless telecommunications and surveillance networks;
- Certain identification devices (RFID);
- Radars (military, aerial, kinetic, meteorological);
- Household appliances and consumer electronics (microwave ovens, cathode ray tubes, induction hobs, etc.);
- Store theft detection barriers.

The development of wireless telecommunications has greatly increased the presence of artificial electromagnetic waves in the environment in the frequency bands authorized for civil and military domains. For example, according to a recent study (2018) published by The Lancet, levels of exposure to radiofrequency electromagnetic radiation around the 1 GHz frequency band, mainly used for wireless communications, increased approximately 1018 times compared to natural levels, extremely low [24] [25]:

Electronic equipment without a radio transmitter (same for transmitters outside their assigned frequency bands) produces unwanted electromagnetic radiation (interference). These are limited by electromagnetic compatibility regulations and lower levels than those authorized for voluntary transmitters.

3. Theoretical Models

3.1. Main Interactions between Electromagnetic Fields and Living Matter

Actions and Effects on the Human Body

To be realistic in our research, we will highlight the physical laws in particular: Maxwell-Faraday:

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{1}$$

Maxwell-Ampere:

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}_c + \frac{\partial \boldsymbol{D}}{\partial t} \tag{2}$$

Maxwell-Gauss:

$$\nabla \cdot \boldsymbol{D} = \rho \tag{3}$$

Ohm's Law:

$$\boldsymbol{j} = \sigma \boldsymbol{E} \tag{4}$$

$$\boldsymbol{B} = \mu_0 * \boldsymbol{H} \tag{5}$$

$$\boldsymbol{D} = \varepsilon_0 * \boldsymbol{E} \tag{6}$$

to explain the actions and effects of electromagnetic waves on the human body.

Interactions between Electromagnetic Fields and Living Matter

Several interactions can unfold when one often exposed to an electromagnetic field. This leads to short-term, direct (biological responses), or indirect effects. According to the WHO, the current state of scientific knowledge does not demonstrate the long-term dangerousness of exposure to low-intensity electromagnetic fields. The interactions between electromagnetic waves and the human body are complex and depend on a large number of factors related to the characteristics of the wave and the biological tissue encountered. An electromagnetic field comprises two components: (an electric field and a magnetic field) thus, the nature of the interactions is different for each of these components [26]. The importance of these interactions depends on:

- The intensity;
- The frequency;
- The orientation of the electromagnetic field to which the tissue is exposed;
- The geometry of the fabric and its electromagnetic characteristics: Magnetic Permeability (μ), Dielectric Permittivity (ε), conductivity (σ).

The coupling between the field and the body, that is to say: tissues, organs, etc.

Interaction between Electric Field and Living Matter

- Dielectric Permittivity:

It describes the response of a material under the action of the electric field. The different tissues that make up the human body each have their permittivity. Since the body is essentially made up of water, the permittivity of a large number of organs happens to be close to that of water, which is 80 times greater than that of air. It is for this reason that the presence of a human body modifies the distribution of the electric field, this field can be defined in the air and the human body as follows see Figure 3 below [26]:

$$\boldsymbol{E} = \frac{\boldsymbol{D}}{\varepsilon_0} \quad \text{(In the air)} \tag{7}$$

In the presence of a human body having a permittivity ε_r, the field $\boldsymbol{E}$ undergoes a modification such that:

$$\boldsymbol{E} = \frac{\boldsymbol{D}}{\varepsilon_r \varepsilon_0} \quad \text{(In the presence of a human)} \tag{8}$$

- Creating a Current:

The electric field causes electric charges to move within a material. According to Coulomb's law, this field can be defined as:

$$\boldsymbol{F} = Q\boldsymbol{E} \tag{9}$$

The field being derived from the potential, therefore:

$$\boldsymbol{E} = -\nabla U \tag{10}$$

The conductivity of the human body being low, few charges are involved. In the case of a static field, the charges are concentrated on the surface of the body.

$$\boldsymbol{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P} \tag{11}$$

With:

$\boldsymbol{D}$: Electrical Displacement in C/m^2;

$\boldsymbol{P}$: Electrical Polarization in C/m^2;

$\boldsymbol{E}$: Electric Field in V/m.

Applying the normal vector in Equation (11), we get:

$$\boldsymbol{nD} = \varepsilon_0 \boldsymbol{nE} + \boldsymbol{nP} \tag{12}$$

From the Equation (12) we get the electric field:

$$\varepsilon_0 \boldsymbol{nE} + \boldsymbol{nP} = \boldsymbol{nD} \tag{13}$$

$$\varepsilon_0 \boldsymbol{nE} = \boldsymbol{nD} - \boldsymbol{nP} \tag{14}$$

The normal of the electric field gives:

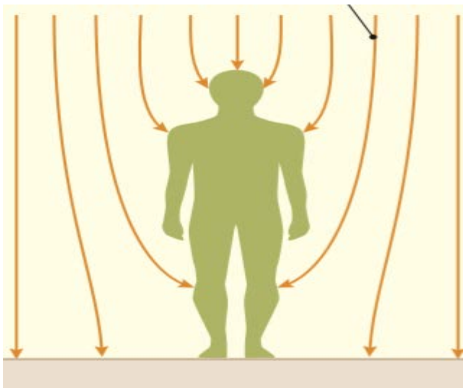

Figure 3. Perturbation of a static electric field in the presence of a body.

$$\boldsymbol{nE} = \frac{\boldsymbol{nD} - \boldsymbol{nP}}{\varepsilon_0} \tag{15}$$

Then multiply the two sides of Equation (15) by the normal vector $\boldsymbol{n}$, we get:

$$\boldsymbol{n} \cdot \boldsymbol{n} \cdot \boldsymbol{E} = \left(\frac{\boldsymbol{nD} - \boldsymbol{nP}}{\varepsilon_0} \right) \boldsymbol{n} \tag{16}$$

Gold: $\boldsymbol{n} \cdot \boldsymbol{n} = 1$

So the electric field is:

$$\boldsymbol{E} = \left(\frac{\boldsymbol{nD} - \boldsymbol{nP}}{\varepsilon_0} \right) \boldsymbol{n} \tag{17}$$

Moreover:

$\boldsymbol{nD} = \sigma$: Actual surface load (18);

$\boldsymbol{nP} = -\sigma'$: Fictitious surface load (19).

By replacing the expressions (18) and (19) in Equation (17), we obtain:

$$\boldsymbol{E} = \left(\frac{\sigma + \sigma'}{\varepsilon_0} \right) \boldsymbol{n} \tag{20}$$

Considering the relative permittivity ε_r of living matter, the electric field on the surface of human skin will be:

$$\boldsymbol{E}_n = \left(\frac{\sigma + \sigma'}{\varepsilon_r \varepsilon_0} \right) \boldsymbol{n} \tag{21}$$

This equation shows that when a human body is exposed to an electric environment (electric field), the electric charges are concentrated on the surface of its skin (see Figure 3). In the case of a time-varying electric field, the orientation of the field periodically reverses and the charges thus move in one direction and the other. So an alternating current is created.

First case:

$$\boldsymbol{E} = K \frac{Q}{r^3} \boldsymbol{r} \tag{22}$$

$$Q = \frac{r^3}{\boldsymbol{r}} \frac{\boldsymbol{E}}{K} \tag{23}$$

The electric current generated by the movement of the charges is modeled by:

$$i = \frac{\mathrm{d}Q}{\mathrm{d}t} \tag{24}$$

Substituting Equation (22) into (24), we get:

$$i = \frac{r^2}{K} \frac{\mathrm{d}\boldsymbol{E}}{\mathrm{d}t} \tag{25}$$

Second case:

If we apply the divergence operator to the third equation and we use the partial derivative to time of the second we obtain the:

$$\nabla \cdot j = -\frac{\partial \rho}{\partial t} \tag{26}$$

This equation is none other than the expression of the local conservation of the charge which therefore appears as a direct consequence of Maxwell's equations. Historically things happened in the opposite order, Maxwell added to the fourth equation a new term (the one on the right) so that the system precisely allows the conservation of the electric charge. This new term is homogeneous with a current density but it is not associated with a mechanical displacement of material charges. The human body behaves in dynamic phenomena like a material medium. In a dynamic system, it is the flow of the total current that is conserved.

$$\boldsymbol{j} = \varepsilon_r \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} \tag{27}$$

Equations (25) and (27) show that a time-varying electric field induces an alternating current in the human body (see **Figure 4**).

So we can say that the higher the conductivity of tissue, the less it opposes the passage of this current. This is why it is said that the passage of such a current can cause biological effects.

- Heating by dielectric losses

The electric field also interacts with polar molecules like water molecules. These molecules have the particularity of presenting a dissymmetry of charges and thus have a negative pole and a positive pole. In an electric field, such dipoles orient themselves according to the direction of this field. In the case of a time-varying electric field, the molecules periodically move in one direction and then in the other. This movement has the effect of heating the material by friction. So the higher the frequency, the faster the movement, making the heating more important with a strong influence on the intensity of the field. This heating can cause an increase in tissue temperature (see **Figure 5**). As the different tissues that make up the human body have permeability close to that of air, the body is thus found to be a little disturbed by the magnetic field.

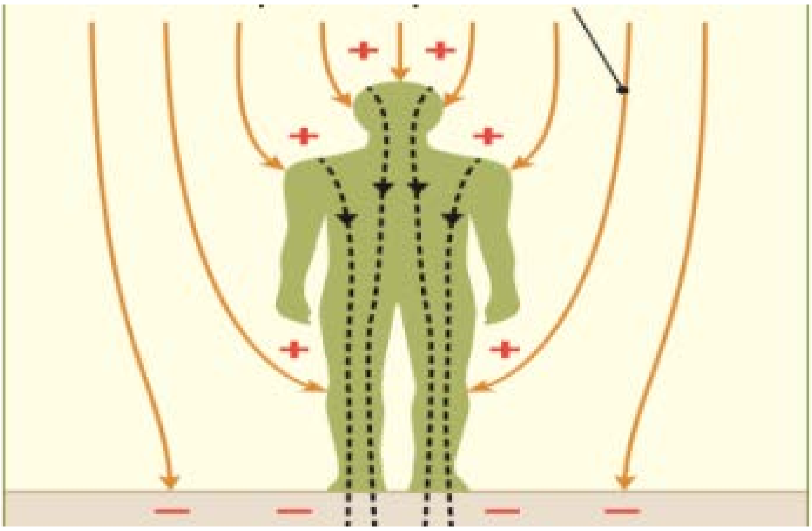

Figure 4. Creation of a current in the body due to the presence of a variable electric field.

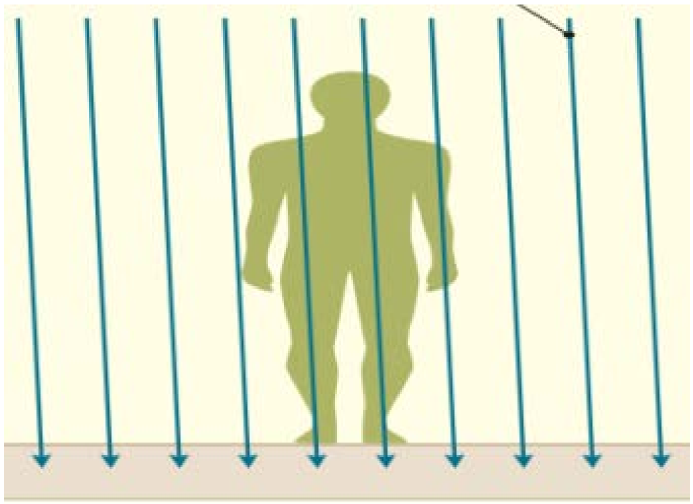

Figure 5. Absence of disturbance of a magnetic field in the presence of a body.

3.2. Modeling of Biological Tissues under the Effect of the Electric Field

Humans live in an electromagnetic environment created by many field sources. These sources can have very different characteristics of frequency, voltage levels, current, or power [26]. They come in various forms such as power lines, telecommunication relays, induction welding tools, mobile phones, or household appliances (hair dryers, induction hob, microwave ovens) [27]. In many situations, the presence of the human body in the radiation area of the source does not affect the power emitted. If the source of the electromagnetic field is known (following in situ measurements or a prior calculation), it is possible not to explicitly model the source but only the human body [28]. This feature is often leveraged in models to limit their complexity [29].

The difficulties in modeling human exposure to electromagnetic fields are due to the particular electrical and geometric properties of the body and the variety of radiation sources.

Different empirical models can be used to approximate the frequency variations of the electrical properties of the cells. Electrical modeling of cells was first proposed by R. Höber in the 1910s, who studied the evolution of the resistivity of a blood sample at low and high frequencies. As a result of these early observations, several electrical models of the cell were constructed in the mid-twenty-second century, such as the model of Fricke, Debye, and Cole-Cole. These models are still widely used today in studies of the electrical behavior of biological media.

The modeling of the Using chamber made it possible to determine the electrical behavior of the system. This step was necessary to carry out the measurements of the different electrical parameters of the tissue and mainly that of the short-circuit current requiring control of the transepithelial tension. The impedance of the electrode/electrolyte interfaces and the impedance of the biological tissue are the main elements taken into account in this modeling.

In electrophysiology, one of the main techniques for characterizing a biological tissue is the measurement of impedance. This technique, widely used in recent years, has enabled the development of several representative models of the electrical behavior of cells, whose properties are both conductive and insulating. Indeed, the lipid double layer can be considered a capacitor: it causes the accumulation of charges on its surface. On the other hand, the transport proteins allow a conduction current just like the paracellular pathway and are therefore comparable to resistances. On the other hand, all biological tissues because of their heterogeneity have different electrical behavior, for example, epithelia behave differently from cells in suspension. As a general rule, the impedance measurements performed on these biological tissues are made using electrodes interfaced directly with the tissues [30] or through physiological media.

In this article the modeling of human biological tissue based on the equivalent electrical circuit model similar to any dielectric medium and capable of modeling all the associated properties to examine the tissue electrical behavior in the face of frequency variation [31] [32] [33] [34] [35]. This approach allows taking into account on the one hand the physical phenomena of the propagation of an electromagnetic microwave plane wave in the range from 0 to 300 GHz and on the other hand, the experimental values to simulate the relaxations α, β and γ and impedance of the biological tissue facing the variation of the frequency of propagation of the electromagnetic waves to identify the related biological consequences.

Electrical Model of Biological Tissue

From a reliability point of view, this equivalent electronic circuit model reproduces with maximum precision the electrical behavior of biological tissue, without taking into account its internal structure. It also reduces the simulation time and gives the possibility to simulate complex systems like the one under study [36]. The response of a cell in the presence of an electric field depends on two parameters which are the relative dielectric permittivity which reflects the ability to polarize a material by the accumulation of charges and the electrical conductivity which reflects the ability to pass an electric current with minimal losses. The fundamental concepts of dielectric phenomena in biological media and their interpretation of interactions at the cellular level are well established [37] [38]. Based on the work of Professors Schwan [37] [38] and Foster [39], the dielectric properties of cells are frequency dependent and exhibit relaxation and resonance phenomena, which are a function of the different polarizations. The relaxations are named α, β, and γ are more often referred to by the term dispersion because the resulting dielectric absorption is observable over a wide range of frequencies [34] [36] [37] [38] [39].

In **Figure 6**, R: represents the resistance in Ohm per meter [$\Omega \cdot m^{-1}$], G: conductance in $Oh \cdot m^{-1}$ per meter; L: inductance in micro Henry per meter [$mH \cdot m^{-1}$], and C: Capacitance in Pico Faraday per meter [$pF \cdot m^{-1}$] [39]. **Table 1** gathers the values of the parameters R, G, L and C modeled for various media. It is the electrical parameters, used in our model, that make up the electrical circuit as

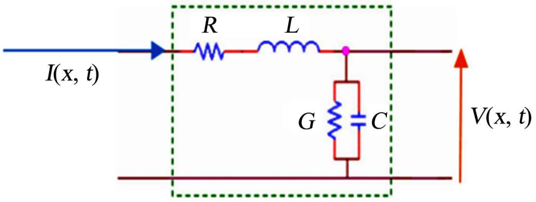

Figure 6. Circuit electronic equivalent of a biological tissue.

Table 1. Values of bioelectric parameters *R*, *G*, *L* and *C*.

Bioelectric Parameters	Blood
R	0
G	2.623
L	1.257
C	6.72

shown in **Figure 6**, which is similar to any biological dielectric medium [39] [40] [41].

The model in **Figure 6** above makes it possible to indirectly obtain the mathematical expressions of the impedance of biological tissues by involving the electrical parameters of the model (*R*, *L*, *C* and *G*) [42] [43] [44] [45] [46]. In order to define the different equations to obtain adequate analytical models of impedance, relaxations called α, β and γ of biological tissue and resonance, physical laws have been put into contribution. Thus, the following mathematical expressions are deduced [47] [48] [49]:

$$Z = \sqrt{\frac{R + jL\omega}{G + jC\omega}} \tag{28}$$

$$\gamma = \sqrt{(R + jL\omega)\cdot(G + jC\omega)} \tag{29}$$

$$\gamma = \alpha + j\beta \tag{30}$$

$$\alpha = R_e[\gamma] \tag{31}$$

$$\beta = Im[\gamma] \tag{32}$$

Indeed, for $R = 0$ Ohm per meter [$\Omega\cdot m^{-1}$] Equations (28) and (29) can be transformed as follows:

$$Z = \sqrt{\frac{jL\omega}{G + jC\omega}} \tag{33}$$

Either $Z = \sqrt{\dfrac{jL\omega(G - jC\omega)}{G^2 + (C\omega)^2}}$.

We can also have:

$$Z = \sqrt{\frac{LC\omega^2}{G^2 + (C\omega)^2} + j\frac{LG\omega}{G^2 + (C\omega)^2}} \tag{34}$$

Let us put:

$$\frac{Lc\omega^2}{G^2+(C\omega)^2}=a \tag{35}$$

$$\frac{LG\omega}{G^2+(C\omega)^2}=b \tag{36}$$

The expression (34) therefore becomes:

$$Z=\sqrt{a+jb} \tag{37}$$

Equation (37) represents the complex form of bio-impedance that is the subject of our investigation. And the relaxation γ for $R = 0$ Ohm per meter [$\Omega\cdot m^{-1}$] is:

$$\gamma=\sqrt{(jL\omega)\cdot(G+jC\omega)} \tag{38}$$

Either:

$$\gamma=\sqrt{\left(-LC\omega^2\right)+j\left(LG\omega\right)} \tag{39}$$

Let us pose again:

$$-LC\omega^2=a' \tag{40}$$

$$LG\omega=b' \tag{41}$$

Hence, Equation (39) becomes:

$$\gamma=\sqrt{a'+jb'} \tag{42}$$

To extract the square roots of $(a+jb)$ and $(a'+jb')$, we will start from the following equality:

$$\sqrt{a+jb}=X+jY \tag{43}$$

Let's square this equality and solve the resultant with respect to X and Y.

$$a+jb=(X+jY)^2=X^2-Y^2+j2XY \tag{44}$$

The method of undetermined coefficients makes it possible to find the following system of equations:

$$\begin{cases} X^2-Y^2=a \\ 2XY=b \end{cases} \tag{44a}$$

The application of the method by addition, by considering the sum of the squares of the equations of the system, gives:

$$\begin{cases} a^2=X^4+Y^4-2X^2Y^2 \\ b^2=4X^2Y^2 \end{cases} \tag{45}$$

Either:

$$a^2+b^2=X^4+Y^4+2X^2Y^2=\left(X^2+Y^2\right)^2 \tag{46}$$

The square root of Equation (46) is equal:

$$\sqrt{a^2+b^2}=X^2+Y^2 \tag{47}$$

The system of equations thus transformed can be written as:

$$\begin{cases} X^2 - Y^2 = a \\ X^2 + Y^2 = \sqrt{a^2 + b^2} \end{cases} \tag{48}$$

By the addition method, we get: $2X^2 = a + \sqrt{a^2 + b^2}$

From where:

$$X = \pm\sqrt{\frac{1}{2}\left(a + \sqrt{a^2 + b^2}\right)} \tag{49}$$

Similarly:

$$2Y^2 = -a + \sqrt{a^2 + b^2}$$

From where:

$$Y = \pm\sqrt{\frac{1}{2}\left(\sqrt{a^2 + b^2} - a\right)} \tag{50}$$

By substituting the relations (49) and (50) in (43), we obtain:

$$\sqrt{a + jb} = X + jY = \pm\frac{1}{\sqrt{2}}\left[\sqrt{\sqrt{a^2 + b^2} + a} + j \text{ sign of } b\sqrt{\sqrt{a^2 + b^2} - a}\right] \tag{51}$$

where sign of $b = \begin{cases} 1 \ \text{ si } b > 0 \\ 0 \ \text{ si } b = 0 \\ -1 \ \text{ si } b < 0 \end{cases}$.

Given that the parameter $b>0$ for the case studied in this article and considering the positive part, the bio-impedance can be written as follows:

$$b = Z = \sqrt{a + jb} = X + jY = \frac{1}{\sqrt{2}}\left[\sqrt{\sqrt{a^2 + b^2} + a} + j\sqrt{\sqrt{a^2 + b^2} - a}\right] \tag{52}$$

Either:

$$\begin{aligned} Z &= X + jY \\ &= \frac{1}{\sqrt{2}}\left[\sqrt{\sqrt{\left(\frac{Lc\omega^2}{G^2 + (C\omega)^2}\right)^2 + \left(\frac{LG\omega}{G^2 + (C\omega)^2}\right)^2} + \frac{Lc\omega^2}{G^2 + (C\omega)^2}}\right. \\ &\quad \left. + j\sqrt{\sqrt{\left(\frac{Lc\omega^2}{G^2 + (C\omega)^2}\right)^2 + \left(\frac{LG\omega}{G^2 + (C\omega)^2}\right)^2} - \frac{Lc\omega^2}{G^2 + (C\omega)^2}}\right] \end{aligned} \tag{53}$$

$$\begin{cases} X = \frac{1}{\sqrt{2}}\sqrt{\sqrt{\left(\frac{Lc\omega^2}{G^2 + (C\omega)^2}\right)^2 + \left(\frac{LG\omega}{G^2 + (C\omega)^2}\right)^2} + \frac{Lc\omega^2}{G^2 + (C\omega)^2}} \\ Y = \frac{1}{\sqrt{2}}\sqrt{\sqrt{\left(\frac{Lc\omega^2}{G^2 + (C\omega)^2}\right)^2 + \left(\frac{LG\omega}{G^2 + (C\omega)^2}\right)^2} - \frac{Lc\omega^2}{G^2 + (C\omega)^2}} \end{cases} \tag{54}$$

Similarly, the relaxation γ is:

$$\gamma = \sqrt{a' + jb'} = \alpha + j\beta = \frac{1}{\sqrt{2}}\left[\sqrt{\sqrt{a'^2 + b'^2} + a'} + j\sqrt{\sqrt{a'^2 + b'^2} - a'}\right] \tag{55}$$

Either:

$$\gamma = \sqrt{a' + jb'} = \alpha + j\beta = \frac{1}{\sqrt{2}}\left[\sqrt{\sqrt{\left(LC\omega^2\right)^2 + \left(LG\omega\right)^2} - LC\omega^2} + j\sqrt{\sqrt{\left(LC\omega^2\right)^2 + \left(LG\omega\right)^2} + LC\omega^2}\right] \quad (56)$$

The analytical models of the named relaxations α and β of the biological tissue can be deduced as follows:

$$\begin{cases} \alpha = \dfrac{1}{\sqrt{2}}\sqrt{\sqrt{\left(LC\omega^2\right)^2 + \left(LG\omega\right)^2} - LC\omega^2} \\ \beta = \dfrac{1}{\sqrt{2}}\sqrt{\sqrt{\left(LC\omega^2\right)^2 + \left(LG\omega\right)^2} + LC\omega^2} \end{cases} \quad (57)$$

Assuming that $\left(C\omega\right)^2 \gg G^2$, the relaxation parameters of the biological tissue under the effect of the electromagnetic field can be modeled in the following compact forms:

$$\begin{cases} \alpha = \sqrt{\dfrac{L \cdot C}{2}} \cdot \omega\sqrt{\left(\omega - 1\right) \cdot C} \\ \beta = \sqrt{\dfrac{L \cdot C}{2}} \cdot \omega\sqrt{\left(\omega + 1\right) \cdot C} \end{cases} \quad (58)$$

4. Simulation

4.1. Results

Considering the range of frequencies from 0 to 300 Gigas Hertz [Ghz] of propagation of electromagnetic waves in human biological tissue, the bioelectrical parameters presented in **Table 1**, and the model of the tissue under the effect of the electromagnetic field. The results of the simulation are presented in **Figures 7-11**. **Figure 12** and **Figure 13** present the results obtained experimentally in the work of Julien MATHIEU [50] [2009] and QUIM CASTELLVI [2014] [51]. Then, **Figure 14** and **Figure 15** below show the results of the phenomenon of dispersion of the biological tissue with respect to the variation of the frequency of the electromagnetic fields.

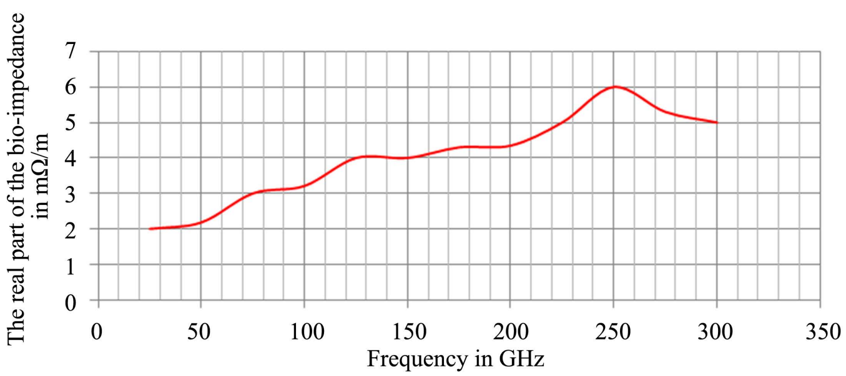

Figure 7. The real part of the bio-impedance of blood as a function of the propagation frequency of the electromagnetic field.

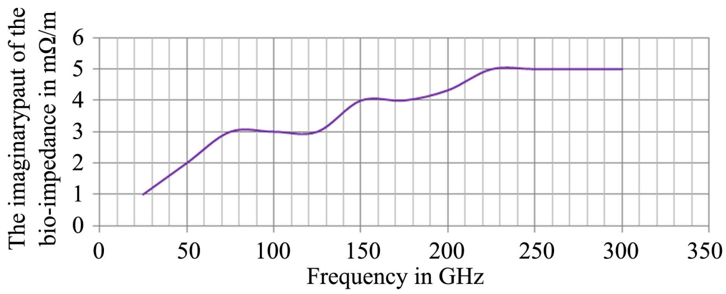

Figure 8. The imaginary part of the bio-impedance of blood as a function of the propagation frequency of the electromagnetic field.

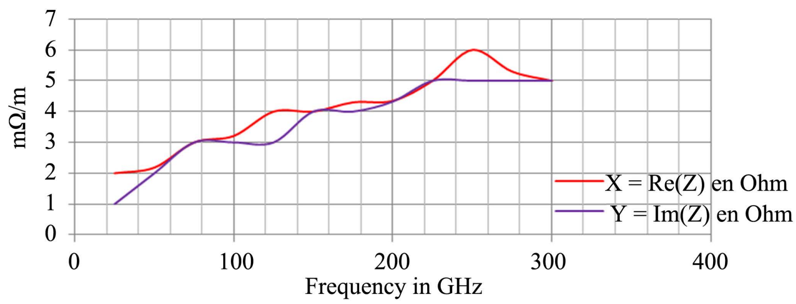

Figure 9. Superposition curve of $X = Re(Z)$ and $X = Im(Z)$ of blood as a function of the propagation frequency of the electromagnetic field.

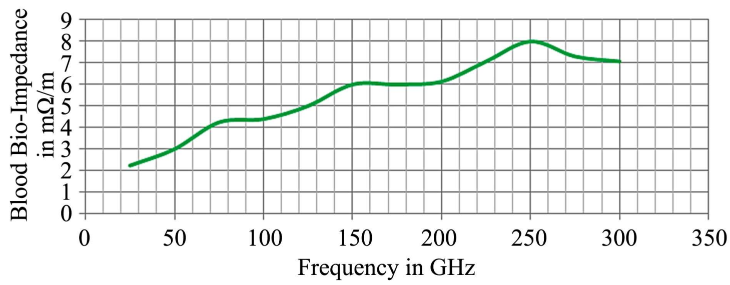

Figure 10. Blood bio-impedance as a function of electromagnetic field propagation frequency.

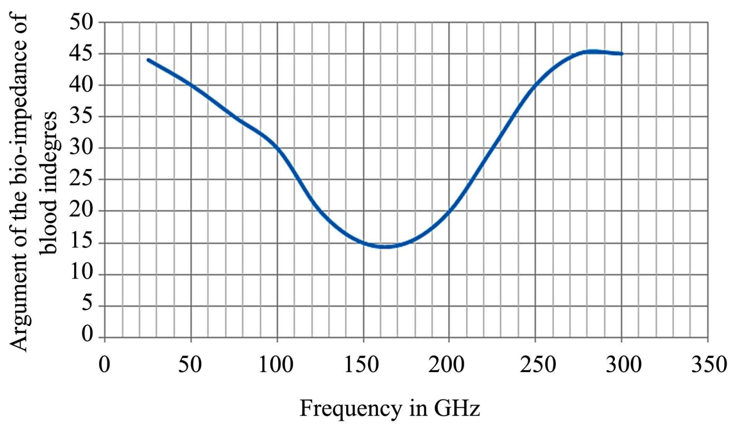

Figure 11. Argument of blood impedance as a function of electromagnetic field propagation frequency.

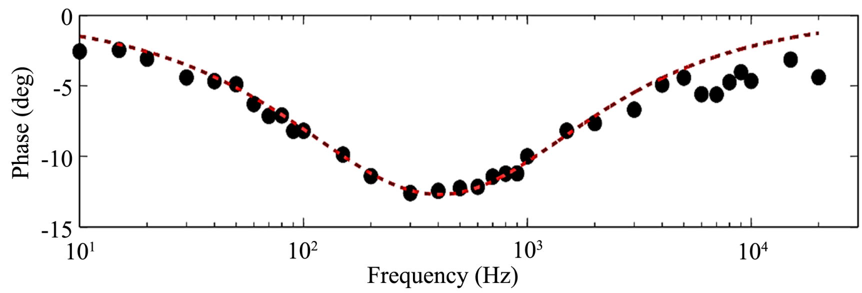

Figure 12. Argument of blood impedance as a function of frequency: result obtained by Julien MATHIEU (2009) [50].

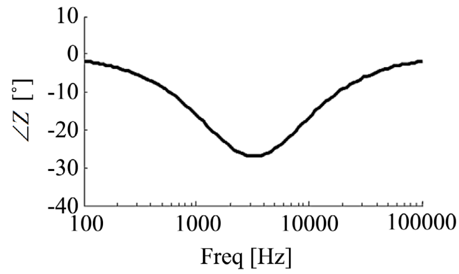

Figure 13. Plot of a classic bio-impedance phase [51].

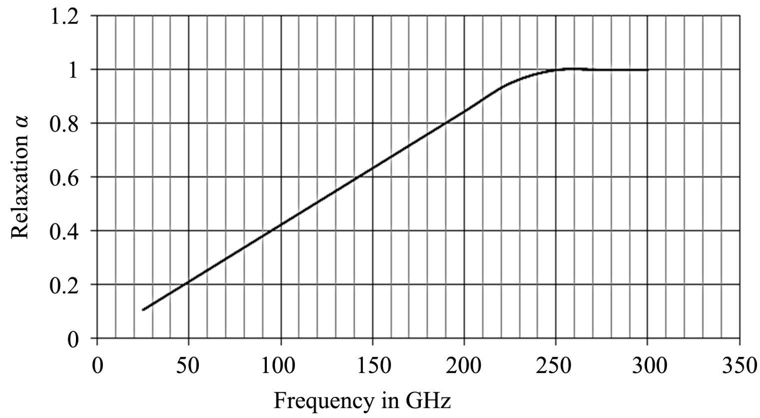

Figure 14. Relaxation α in function of frequency.

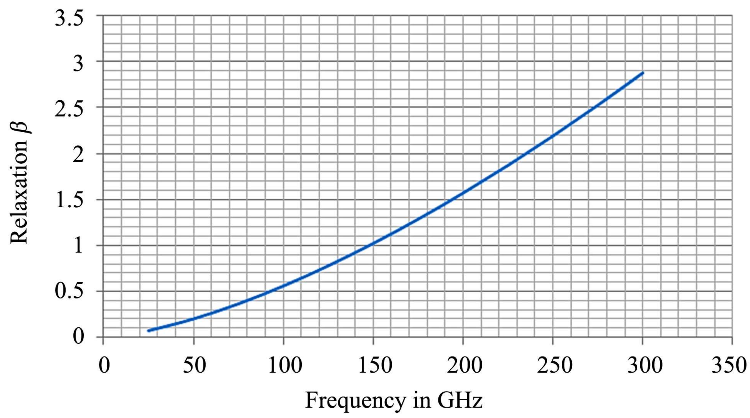

Figure 15. Relaxation β in function of frequency.

4.2. Discussions

According to the biological tissue model studied in this article, Figure 7 and Figure 8 show that the real part and the imaginary part of the bio-impedance are linear functions of the propagation frequency of the electromagnetic field to which the tissue is subjected. The superposition of these two figures is presented in Figure 9. We observe the variation of these parameters as a function of the frequency of the electromagnetic field. This can have biological consequences on humans. The use of high frequencies, of the order of tens of gigahertz and more, can cause non-thermal effects that are harmful to the health of an exposed biological system. This depends on the frequency, the intensity of these waves, and the duration of exposure to them.

The linearity of bio-impedance with respect to frequency and in the range of 30 - 250 GHz is shown in Figure 10, this simulation result shows the linear behavior of the tissue. These observations suggest that the tissue can be physiologically stressed at high frequencies. Note that any stimulation of a cell, a tissue, or an organism, whether by electromagnetic waves or by any other exciter of a given nature, can be accompanied by a normal adaptive response from it: c is a biological consequence. A biological effect can however endanger the normal functioning of an organism when its physiological response capacities in response to the action of the external agent are exceeded: A so-called health effect then occurs and health is hampered. Figure 11 below gives the behavior of the bio-impedance phase and however confirms the results obtained experimentally in the work of Julien MATHIEU (2009) [50] and QUIM CASTELLVI (2014) [51], see Figure 12 and Figure 13.

Figure 14 and Figure 15 show the dispersion phenomena characterized by the factor γ. This depression is known to be the result of α and β dispersion phenomena causing the bio-impedance to vary in the frequency domain. Is a consequence of the linear behavior of bio-impedance. The understanding of α dispersion remains incomplete (Schwan, 1994). Various mechanisms and elements contribute to this frequency dependence and three points can be distinguished (Schwan & Takashima, 1993).

The effects of electromagnetic fields are functions of the type of field encountered, and their interactions are at the origin of direct, indirect, long-term effects, etc.

In the long term, the low-frequency effects are studied based on several epidemiological studies relating to groups of children residing near HV lines and other elderly people (see the studies carried out by Professor Anthony Nzao in DR Congo on people living near the HV line). The International Agency for Research on Cancer (IARC) has also classified extremely low-frequency electromagnetic fields as possibly carcinogenic to humans.

As far as the direct effects are concerned, the interactions are dependent on the frequency of the applied field. The known short-term biological and health effects are the effects of electrical stimulation of all tissues of the central and peripheral nervous system due to induced currents at low frequency ($f < 10$ MHz), on the other hand, the thermal effects in biological tissues are caused by electromagnetic fields with a frequency greater than or equal to 100 Hz. Thus, the effects which are caused by electromagnetic fields with a frequency ranging from 100 Hz to 10 MHz are due to induced currents.

Among the many biological effects observed, some can have harmful consequences on health. At low frequencies, stimulation of nerves and muscles can lead to muscle contractions and parasitic nerve stimulation. High-frequency fields primarily generate localized heating or hyperthermia. Exposure to electromagnetic radiation must be considered differently depending on whether it is a mobile or a base station (relay antenna). The mobile telephone is characterized by a lower power emitted than a base station, but its immediate proximity to the body, in particular the cranial box, means that the power absorbed by the user is generally greater with mobile than with a base station. Indeed, the base station emits a strong output power, but the field quickly loses its intensity as the distance increases and is attenuated by the residential walls. It should be noted that a mobile phone emits an electromagnetic field mainly when the device is in communication, some studies have been carried out and have defined sensory type effects where at a certain frequency the level of exposure has health effects are weaker.

In a static field, during an exposure of the head associated with movements, these effects can create illnesses on living beings such as dizziness, nausea or a metallic taste sensation in the mouth can be felt, at a frequency of 1 to 400 Hz, retinal phosphenes may occur, as well as temporary minor changes in certain brain functions. And for the radar (the pulsed fields) having a frequency that varies between 300 Hz and 6 GHz, an auditory effect (click) can be perceived during the exposure of the head, whereas a base station of a relay antenna emits a permanent electromagnetic field 24 hours a day, which can be dangerous for living beings if they are outside dwelling houses and next to relay antennas.

So, this can generate several types of diseases as mentioned above. Electromagnetic fields can cause indirect effects that can cause harm to people or aggravate a dangerous work situation. In a static field, forces of attraction and rotation can be exerted on ferromagnetic objects that are worn by the worker: implanted or non-implanted medical devices, and jewelry, which are placed in a work environment (tools, machines, etc.). These forces can generate displacements, even projections, of these metallic elements and cause electric shocks or even burns which can cause during contact with a conductive object subjected to an electromagnetic field when the worker or the object is not grounded.

Electromagnetic waves can cause several harmful effects on living beings which several studies have confirmed and others so far contradict. These effects are as follows: Childhood cancer, cancer in adults, leukemia, brain cancer and reproductive and developmental disorders.

5. Conclusions

In this article we have chosen the modeling approach based on the electrical circuit of a human biological tissue, taking into account on the one hand the physical phenomena of the propagation of an electromagnetic microwave plane wave and on the other hand the experimental values in order to simulate the relaxations α, β and γ, and the impedance of the biological tissue faced with the variation in the frequency of propagation of the electromagnetic waves.

The proposed work mainly aims to provide arguments to justify the relevance of the results of studies of the interaction between electromagnetic fields and the human body. We have tried to take advantage of the many advantages of this method, namely the reduction of simulation time, the possibility of simulating complex systems like the one under study.

The simulation results obtained from Equations (21), (25), (27), (28) to (32) have been compared with those obtained experimentally in the work of Julien MATHIEU and QUIM CASTELLVI and can also find applications in the precise electrical characterization of biological media and in setting new standards for human exposure to electromagnetic fields. The results obtained in the literature show the linear dependence of the bio-impedance with respect to the frequency. These observations suggest that the tissue can be physiologically stressed at high frequencies. This can have biological consequences on humans.

Of all the analyzes and modeling, Maxwell's equations can also be used in detail to model human biological tissues exposed to microwave electromagnetic waves by taking into account all of these parameters.

Compared to epidemiological studies, we were able to identify the biological consequences of electromagnetic pollution for human beings. They have the advantage of focusing on the specific effects of exposure on health. The dilemma in the evaluation of epidemiological studies is to be critical enough to detect all potential biases and their effects, while interpreting the results obtained with caution. Three risks to human health have been particularly studied in epidemiological studies: cancers, reproductive disorders and neurobehavioral disorders. And the various effects and consequences on human health in relation to its environment have been studied such as: long-term effects, direct effects, indirect effects, effects on the cell, effects on biological systems, EMC and cancer, the effects observed in human, the risk of cancer in children, the risk of cancer in adults, reproductive disorders.

However, the results obtained are usable and can help to reinforce the validity of the results of epidemiological and experimental studies. These will have to be reinforced by multiple tests on varied populations regularly subjected to various radiations and for periods ranging from zero to human life expectancy.

A direct prospect of this study is the application of one of the methods that we used, that is to say the electronic circuit method to enrich the models of existing human biological tissues with a view to the simulation of impact of electromagnetic waves on living beings living near relay antennas. Other electromagnetic parameters could be taken into account to develop an electrical model of biological tissue in a more complex and complete form. This method is also intended to be tested on other tissues, possibly outside the framework of the biological tissues treated in this article. The complete modeling of the brain, heart, faith and simulation constitutes a much broader perspective and can also be analyzed in a complete way from the MoM method.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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