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Analysis of the Modeling and Biological Consequences of the Electrical Activity of the Human Brain Subjected to 5G Electromagnetic Waves Using Maxwell's Equations

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Abstract

The main objective proposed in this article is to provide explanations that can justify the validity of the results of the studies of the interaction between electromagnetic fields and the human body, while putting the direct applications in the characterization and modeling of the macroscopic electrical properties of biological environments and evaluating the effects of fields induced by sources of electromagnetic radiation on the human body to establish new standards on human exposure to electromagnetic fields. To do this, we took into account, on the one hand, the physical laws based on the Maxwell and Kirchhoff equations, with the different physical phenomena of propagation of a 5G electromagnetic plane wave and on the other hand, the experimental values that can allow us to model the electrical behavior of the human brain under the influence of 5G electromagnetic field the Morris-Lecar model is used because it has the ease of assimilating brain electrical activity. This model uses the characteristic impedance of the dielectric support and allows us to evaluate the influence of the current induced by microwave electromagnetic waves in the brain system studied. The results of 2D simulations obtained from computer tools demonstrate that 5G electromagnetic waves can cause the modification of brain rhythm, the disruption of neuronal communication, oxidative stress and the opening of various ion channels that govern the functionality of the brain system. This modification can have a very significant influence on the life of the brain's biological tissue since electromagnetic waves can influence the frequency and amplitude of electromagnetic signals in the brain and this can affect cognitive functions in the brain.

Keywords

Modeling, 2D Simulations, 5G Electromagnetic Field, Biological Tissue, Brain Electrical Activity, Morris-Lecar Model, Neurosciences Models, Maxwell's Equations, Kirchhoff Equations

1. Introduction

Telecommunications networks use radiofrequency electromagnetic fields for wireless communication [1] [2]. They have evolved and several generations have followed one another. 5G telecommunications networks operate at frequencies not previously used by previous generations and considerably multiply the emission sources, which modifies the exposure of fauna and flora to these waves [1]. Since the mobile phone is a central element of our daily lives, its extensive use is accompanied by exposure to RF-EMF. It can have consequences on living beings, given the proximity of the 5G mobile phone to the user's head. This exposure raises many questions about its effects on health and more particularly on the brain as the organ most exposed during phone calls [3]. Let us also point out that there is a close link between IoT and 5G, but this link has not only advantages but also disadvantages, because 5G offers capabilities that significantly improve the operation and efficiency of IoT applications at several levels [3] [4].

This link also allows the rapid transfer of large amounts of data, which is essential for IoT devices that collect and analyze data in real-time, that is, the time it takes for a signal to go from one point to another. This is important for IoT applications requiring instantaneous responses, such as autonomous cars, connected health devices, telemedicine, augmented reality, and urban infrastructure management [3]-[5].

We have proposed a mathematical and numerical approach in this article that is both analytical, comparative and critical, whose objective is to model the biological consequences of the electrical activity of the human brain subjected to 5G OEMs [5].

To do this, we implemented the physical laws based on Maxwell's equations and Kirchhoff's laws to model the propagation phenomena of a 5G RF plane electromagnetic wave in the biological environment. The Morris-Lecar model [6]-[9], which takes into account the slowest channel, the leakage current, the calcium channel and the potassium channel, as well as the experimental values taken from the literature, was used to model and simulate the influence of 5G RF OEMs on the electrical activity of the human brain [6] [10] [11]. These models use the characteristic impedance of the dielectric support which makes it possible to evaluate the influence of the current induced by microwave electromagnetic waves in the brain system.

2. Methods

This article aims to demonstrate the validity of the results on the interaction between electromagnetic fields and the human body. The objective is to apply these results to characterising the electrical properties of biological environments and assessing the effects of electromagnetic fields on humans, to establish new exposure standards.

The method used to achieve these objectives considers physical laws, particularly the Maxwell and Kirchhoff equations, as well as 5G electromagnetic wave propagation phenomena, integrating experimental values to model the electrical behaviour of the human brain under a 5G electromagnetic field.

From experimental studies on large axons, mathematical models simulating the behaviour of neurons have been constructed. The most complete model and the closest to biological neurons is the Hodgkin-Huxley (HH) model [6] [10] [11] in 4 dimensions, then come the simplified models in three or two dimensions. The Morris-Lecar (ML) model [11] is a simple two-dimensional model, but it still retains a biophysical meaning. Another advantage of the ML model is that it can present the two different classes of excitable neurons, type I and type II. One might ask what the point of using this simplified model is if we observe the same behaviours? The answer could be that this two-degree-of-freedom model allows us to study mathematically what happens thanks to simplified geometric arguments, a study in the phase plane being then possible. Thus, the electronic realisation of a simplified model requires fewer resources [6] [10] [11].

The Morris-Lecar model is suitable for studying the brain because, although initially developed for barnacle muscle fibers, it captures fundamental principles of neuronal activity, including the generation of action potentials via the dynamics of two types of ion channels (calcium and potassium), making it applicable to more complex neurons and allowing oscillations and synchronization to be modeled at the level of brain networks.

The Morris-Lecar cellular model has limitations such as poor experimental support and oversimplification of neuronal complexity, making it more of a didactic tool than an accurate representation of real neurons. For more realistic alternative models, particularly in humans, we can cite the Hodgkin-Huxley model (which inspired the Morris-Lecar model), but also more elaborate models such as multicompartment models and machine learning-based approaches for a more faithful representation of human neuronal diversity.

The Morris-Lecar model is used for its ability to simulate brain electrical activity. This model assesses the impact of microwave electromagnetic waves on the brain system using the characteristic impedance of the dielectric medium.

To this end, the following aspects frame the structure of this method.

2.1. Modeling the Electrical Activity of the Brain

To model brain electrical activity, Hodgkin-Huxley (1952) [6] [7] introduced this formalism and described the generation of the action potential in the squid axon, it is based on the linear approximation of the ionic currents involved and it does not take into account the spatial dependencies of the membrane potential [8] [9]. This is the fundamental model of neuroscience that involves a transient sodium current, a persistent potassium current and a macroscopic dynamic leakage current of human brain electrical activity at rest, **Figure 1** [6] [10].

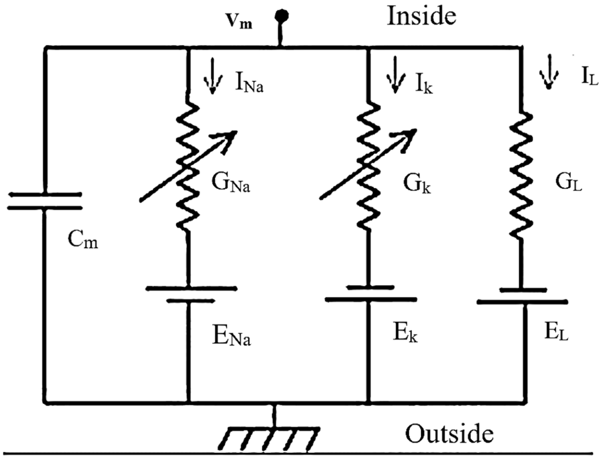


Figure 1. Ionic currents in the Hodgin-Huxley model and Catherine Morris and Harold Lecar [6] [7].

Figure 1 above shows the systems involved in neuroscience describing the membrane potential $v(t)$ of a neuron. They take the form of equations involving the opening $g_i(t)$ of the various ion channels numbered $i = 1, 2, \ldots, I$. The general formulation of the model in **Figure 1** proposed by Hodgin-Huxley and Catherine Morris-Harold Lecar is given by the system of equations below [6].

$$\begin{cases} \dfrac{\mathrm{d}v(t)}{\mathrm{d}t} = \sum\limits_{i=1}^{I} g_i(t)\left(V_i - v(t)\right), \\ \dfrac{\mathrm{d}g_i(t)}{\mathrm{d}t} = \dfrac{G_i\left(v(t)\right) - g_i(t)}{\tau_i\left(v(t), g(t)\right)}, \quad g_i(0) \geq 0, \ i = 1, 2, \cdots, I, \end{cases} \tag{1}$$

With $g = (g_1, \cdots, g_I)$. The quantities V_i, called Nernst reversion potential are given constants. We assume that the functions $G_i(t) > 0$ (the equilibrium opening rates) and τ_i (the characteristic times) are of class C and there exist constants $0 < \tau_- < \tau_+ < \infty$ such that [11]-[13]:

$$\tau_- \leq \tau_i(v, g) \leq \tau_+ . \tag{2}$$

Model (1) is simple and the most used to reproduce experimental observations and phenomena of discharge and cerebral excitability. Many books and "Surveys" deal with theoretical neuroscience, one can consult [6].

Cells are polarized and for to describe this potential difference across the membrane, neuron models are based on the elementary laws of electrical circuits. The cell membrane plays the role of a capacitor and we therefore write [6] [14] [15]:

$Cv(t) = Q(t)$ with C, the capacity, v the potential, Q the electric charge. These parameters are related by the following system of equations:

$$\begin{cases} I(t) = \dfrac{\mathrm{d}Q(t)}{\mathrm{d}t} \\ C\dfrac{\mathrm{d}v(t)}{\mathrm{d}t} = I_{cap}(t) \end{cases} \tag{3}$$

The constant $C = 1\ \mu\text{F/cm}^2$ will often be taken equal to 1 in the rest of this article [6] [7]. Then we consider that currents through the membrane result (in parallel) from the capacitance effect and the opening of ion channels (Calcium Ca, potassium K, and chloride Cl^- associated with the leakage current). Each ionic current Ii results from a resistance modulated by the opening of the channel that we describe by Ohm's law, $v = R.I$, from which the relation, considering that a current I_{stim} is applied.

$$\begin{cases} I_{cap}(t) + \sum_i I_i(t) = I_{stim}, \\ I_i(t) = g_i\left(v(t) - V_i\right), \\ g_i = \dfrac{1}{R_i} \end{cases} \tag{4}$$

We can then assume that $g_i(t) \equiv G_i(v(t))$ and reduce the complexity of the model (1) [6]. Typically, only the slowest channel is kept and, for the electrical activity of muscle cells, a proven model consists of keeping only the leak current, the calcium channel and the potassium channel [6] [7]. The model proposed by Catherine Morris and Harold Lecar under this hypothesis can be written in this form [6] [15]:

$$\begin{cases} \dfrac{\mathrm{d}v(t)}{\mathrm{d}t} = I_{stim} + G_L\left(V_L - v(t)\right) + G_{Na}\left(v(t)\right)\left(V_{Na} - v(t)\right) + g_K(t)\left(V_K - v(t)\right), \\ \dfrac{\mathrm{d}g_K(t)}{\mathrm{d}t} = G_K\left(v(t)\right) - g_K(t). \end{cases} \tag{5}$$

The numerical values of the parameters v_i allow us to determine the G_i through the following relation:

$$G_i(v) = \frac{\tilde{G}_i}{1 + \exp\left(\dfrac{v_{1/2} - v}{k}\right)} \tag{6}$$

The main ingredients of the genesis of an action potential by a nerve cell (mainly the temporal separation between the two variables and the cubic shape of the v nuclein) appeared in two-dimensional models and captured by the FHN model [6] [15]-[18].

2.2. Modeling of Emissions Radiated by GSM Telephones

Starting from the wave equations below obtained from Maxwell's equations. For the electric and magnetic fields, we are interested in, the wave equations, at a point $\boldsymbol{r}$ and at time t, are given respectively by [1]:

$$\nabla \times \nabla \times \boldsymbol{E}(\boldsymbol{r}, t) + \mu_0 \varepsilon_0 \frac{\partial^2}{\partial t^2} \boldsymbol{E}(\boldsymbol{r}, t) = \mu_0 \frac{\partial^2}{\partial t^2} \boldsymbol{J}(\boldsymbol{r}, t) \tag{7}$$

$$\nabla \times \nabla \times \vec{H}(\boldsymbol{r}, t) + \mu_0 \varepsilon_0 \frac{\partial^2}{\partial t^2} \boldsymbol{H}(\boldsymbol{r}, t) = \mu_0 \nabla \times \boldsymbol{J}(\boldsymbol{r}, t) \tag{8}$$

where $\boldsymbol{E}$ is the electric field, $\boldsymbol{H}$ is the magnetic field and μ_0 and ε_0 are the magnetic permeability and electric permittivity of air (vacuum), respectively. The wave equations are written as follows [1] [2]:

$$\Delta \boldsymbol{E}(\boldsymbol{r},t) - \mu_0 \varepsilon_0 \frac{\partial^2}{\partial t^2} \boldsymbol{E}(\boldsymbol{r},t) = \frac{1}{\varepsilon_0} \nabla \rho(\boldsymbol{r},t) + \mu_0 \frac{\partial}{\partial t} \boldsymbol{J}(\boldsymbol{r},t) \tag{9}$$

$$\nabla \times \nabla \times \boldsymbol{H}(\boldsymbol{r},t) + \mu_0 \varepsilon_0 \frac{\partial^2}{\partial t^2} \boldsymbol{H}(\boldsymbol{r},t) = \nabla \times \boldsymbol{J}(\boldsymbol{r},t) \tag{10}$$

The modeling of the radiated emission contribution of each discretization cell takes into account the currents in the structure, obtained by an appropriate method [19]. First, a discretization cell is considered equivalent to a dipole. Then, in this case, only one dimension, which is the length, is considered.

To achieve this goal, two main approaches can be used for such a calculation: the quasi-steady state approximation and the infinitely small dipole approximation [19] [20].

We know that the fields $\boldsymbol{E}(\boldsymbol{r},t)$ and $\boldsymbol{H}(\boldsymbol{r},t)$ can be written in terms of the vector potential $\boldsymbol{A}$ and the scalar potential φ. The notion of potentials has been used in order to simplify the resolution of Maxwell's equations. **Figure 2** below shows the structure of a discretized cell [19] [20].

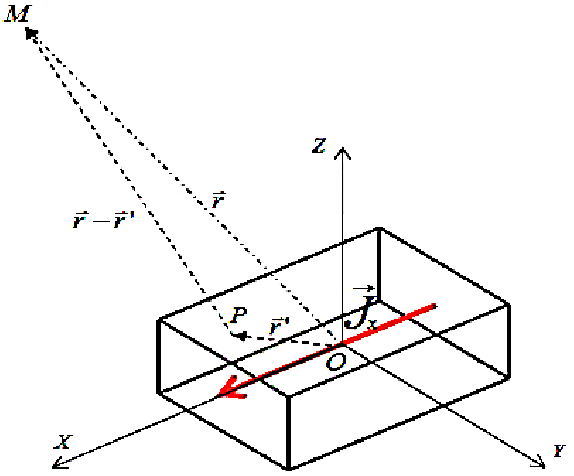


Figure 2. Discretization cell [1].

It is shown that, for a cell crossed by a current and whose section is very small compared to the length, the radiation will be considered equivalent to that generated by an electric dipole. Thus, the vector potential is given by [1]:

$$\boldsymbol{A} = \frac{\mu_0}{4\pi} \cdot I \cdot \int_c \frac{\mathrm{e}^{-jk|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|} \mathrm{d}\boldsymbol{l}' \tag{11}$$

where I is the current through the cell and C is the length.

The radiated emissions are perfectly defined by the magnetic field and the electric field. Using the Lorentz gauge, we can write the electric field as a function of the vector potential alone [19].

$$\boldsymbol{H} = \frac{1}{\mu_0}\nabla \times \boldsymbol{A} \tag{12}$$

$$\boldsymbol{E} = \frac{1}{j\omega\varepsilon_0\mu_0}\nabla \times \nabla \times \boldsymbol{A} \tag{13}$$

We consider the discretization cell presented in **Figure 2**. The vector potential is given by [19]:

$$\boldsymbol{A} = \frac{\mu}{4\pi}\boldsymbol{j}_\gamma \iiint_{v'} \frac{\mathrm{e}^{-jk|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|}\mathrm{d}v' \tag{14}$$

In our 1D case, we consider $\gamma = x$. The vector potential is written:

$$A_x = \frac{\mu}{4\pi} I_x \int_{-dx/2}^{dx/2} \frac{\mathrm{e}^{-jk|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|}\mathrm{d}x' \tag{15}$$

By applying the quasi-steady state approximation to Equation (15), we therefore find:

$$A_x = \frac{\mu}{4\pi} I_x \mathrm{e}^{-jkr} \int_{-dx/2}^{dx/2} \frac{1}{\sqrt{x^2+y^2+z^2}}\mathrm{d}x' \tag{16}$$

The calculation gives:

$$A_x = \frac{\mu}{4\pi} I_x \mathrm{e}^{-jk} \log\left(\frac{x-\frac{dx}{2}+\sqrt{\left(x-\frac{dx}{2}\right)^2+y^2+z^2}}{x+\frac{dx}{2}+\sqrt{\left(x+\frac{dx}{2}\right)^2+y^2+z^2}} \right) \tag{17}$$

The infinitely small dipole approximation is widely used in electromagnetic modeling and especially in the field of antennas. In this case, the length of the dipole is infinitesimally small compared to the wavelength. Typically, it is less than a tenth. Note also that the distance of the observation point from the origin of the dipole is an important parameter in this approximation. The vector potential is written:

$$A_x = \frac{\mu}{4\pi} I_x \frac{\mathrm{e}^{-jkr}}{r} dx \tag{18}$$

In order to improve the calculation precision, we exploit the calculation approach based on the Maclaurin series. This approach is based on the fact that the length of the dipole is infinitely small compared to the wavelength. It resembles the infinitely small dipole approximation which is only a special case of it. Thus, we choose an order higher than the first order for calculation improvement.

By changing the variable ($\alpha = \frac{x'}{\lambda}, \eta = \frac{r}{\lambda}$ et $Q = \frac{x}{\lambda}$) in expression (17), we obtain the integral expression of the potential vector, considering Equation (19) below:

$$\frac{\mathrm{e}^{-jk|\boldsymbol{r}-\boldsymbol{r}'|}}{|\boldsymbol{r}-\boldsymbol{r}'|} = \frac{\mathrm{e}^{-jk\sqrt{(x-x')^2+y^2+z^2}}}{\sqrt{(x-x')^2+y^2+z^2}} \tag{19}$$

The new expression of the vector potential integrating the variable α is of the following form:

$$A_x=\frac{\mu}{4\pi}I_x\int_{-dx/2\lambda}^{dx/2\lambda}\frac{\mathrm{e}^{-j2\pi\sqrt{\eta^2-2Q\alpha+\alpha^2}}}{\sqrt{\eta^2-2Q\alpha+\alpha^2}}\mathrm{d}\alpha \tag{20}$$

Considering $\frac{\mathrm{e}^{-j2\pi\sqrt{\eta^2-2Q\alpha+\alpha^2}}}{\sqrt{\eta^2-2Q\alpha+\alpha^2}}=f(\alpha)$, given that $\alpha\ll1$ Taking into account the dimensions of discretization cells are very small compared to the wavelength, the development of the function $f(\alpha)$ in the form of a Maclaurin series is in the following polynomial form:

$$f(\alpha)=f(0)+f'(0)\alpha+\frac{1}{2}f''(0)\alpha^2+\frac{1}{6}f'''(0)\alpha^3 \tag{21}$$

Moreover, $f'(0)=f'''(0)=0$ because in the calculation of the integral of the polynomial equivalent to f between $-dx/2\lambda$ and $dx/2\lambda$, terms of odd order, in particular those of the first and third order, are zero.

$$\boldsymbol{A}(x,y,z)=\frac{\mu}{4\pi}I_x\left(\frac{1}{2}f(0)\frac{dx}{\lambda}+\frac{1}{24}f''(0)\frac{dx^3}{\lambda^3}\right)\boldsymbol{e}_x \tag{22}$$

It is this last order which makes it possible to improve the precision. The component following ox of the vector potential is written, as in the case of the infinitely small dipole, as a function of the wavelength, of the length of the dipole. The expression of the vector potential is given by:

$$A_x=\frac{\mu}{4\pi}I_x\mathrm{e}^{-jkr}dx\Bigg(\Bigg(\bigg(\frac{1}{r}+\frac{1}{24r^3}\Big(x^2(jkr)^2+\big(3x^2-r^2\big)\big(1+jkr\big)\Big)\bigg)dx^2\Bigg) \tag{23}$$

Determining the radiated emissions of a cabling system involves two main steps: calculating the conducted emissions and deducting the radiated emissions. The first consists of determining for each discretization cell the current passing through it. Then, knowing both the geometry and the current value at each frequency, we use the analytical calculation approach to define the contribution of each of the discretization cells. The EM field at any point in space is the contribution of each cell and it is obtained by summing the different components of the magnetic and electric fields.

2.3. Biological Tissues: Electrical Properties

From an electromagnetic point of view, biological media appear as materials at the same time [21]-[42]:

- ✓ Non-magnetic,
- ✓ Ionic conductors,
- ✓ Lossy dielectrics.

In general, biological tissues have a diamagnetic character. Certain substances such as ferritin, hemosiderin or methemoglobin with a paramagnetic nature are naturally present in the human body [41] [42]. However, the human body is still considered non-magnetic for the study of induced electromagnetic fields, and the magnetic permeability of biological tissues is therefore taken equal to that of a vacuum. Regarding electrical properties, given the chemical composition of biological tissues, the free charges capable of creating conduction currents are ions. These ions can move more or less freely under the effect of an electric field. They are subject to friction forces and stresses due to the structure of the tissues. Consequently, their mobility depends on the frequency of the source field. The presence of electric polar molecules of various sizes and also subject to friction, contributes to giving biological environments a lossy dielectric character. The human body therefore presents highly heterogeneous electrical properties at the microscopic (cellular structures) and macroscopic (organs) levels [41] [42]. The microscopic structure of a tissue can sometimes give it macroscopic anisotropic electrical properties: this is the case of muscles, for example, which are made up of cells that are very elongated in a single direction. In general, to characterize biological environments, we use the notions of conductivity (σ) and relative permittivity (ε_r) such that the density of electric current induced by the $\boldsymbol{j}$ pulsating electric field ω is $\boldsymbol{E}$ [41] [42]:

$$\boldsymbol{j} = \left(\sigma + j\omega\varepsilon_0\varepsilon_r\right)\boldsymbol{E} \tag{24}$$

where ε_0 is the electrical permittivity of the vacuum.

These properties are often derived from macroscopic measurements on a given tissue considered homogeneous (and sometimes anisotropic) [41]-[44]. The conductivity thus defined includes the static conductivity of the medium as well as the effect of dielectric losses. Sometimes, the notions of complex conductivity (σ) or complex relative permittivity (ε_r) are used. The current density and the electric field are then given by the relations:

$$\boldsymbol{j} = \sigma\boldsymbol{E} = \left(\sigma' + j\sigma''\right)\boldsymbol{E} \tag{25}$$

$$\boldsymbol{j} = j\omega\varepsilon_0\varepsilon_r\boldsymbol{E} = j\omega\left(\varepsilon_r' + j\varepsilon_r''\right)\boldsymbol{E} \tag{26}$$

For most tissues [43] [44], it is not possible to carry out measurements allowing electrical characterization in vivo. It is often necessary to perform these in vitro measurements on tissue samples taken from deceased subjects. This very strong constraint poses the problem of conditioning the tissue to be studied. Indeed, the cellular structure can deteriorate rapidly after death, and the electrical properties can vary depending on many parameters that are difficult to control in vitro such as blood supply, hydration level or temperature. This particular distribution of charges at the interfaces results in a very high impedance between the electrode and the biological environment for frequencies below a few kHz. The spectroscopic study of this interface impedance shows that it can be modeled in the form [43]-[45]:

$$Z_i = K\left(j\omega\right)^{-\alpha} \tag{27}$$

With $0 < \alpha < 1$

The electrical characterization of biological media requires the use of a measuring device and a model allowing the extraction of conductivity and permittivity parameters. There are several measurement methods which differ depending on the frequencies studied [43]-[46]. For each method, there are different more or less complex models to represent the measuring device and the sample tested [46]. Different empirical models can be used to approximate the frequency variations of the electrical properties of biological media.

- **Debye Model**

The complex permittivity is expressed in the form [43] [46] [47]:

$$\varepsilon_r = \varepsilon_{r\infty} - j\frac{\sigma}{\omega\varepsilon_0} + \sum_n \frac{\Delta\varepsilon_{rn}}{1 + j\dfrac{\omega}{\omega_n}} \tag{28}$$

where $\varepsilon_{r\infty}$ is the relative permittivity at infinite frequency, ω_n is the characteristic pulsation corresponding to relaxation n, σ is the conductivity at zero frequency and $\Delta\varepsilon_{rn}$ is the permittivity variation for relaxation n. This is the basic model for representing relaxation phenomena.

- **Cole Model Cole**

This model introduces an additional parameter α_n characteristic of the frequency dispersion of each relaxation n [43] [46]-[49]:

$$\varepsilon_r = \varepsilon_{r\infty} - j\frac{\sigma}{\omega\varepsilon_0} + \sum_n \frac{\Delta\varepsilon_{rn}}{1 + \left(j\dfrac{\omega}{\omega_n}\right)^{1-\alpha_n}} \tag{29}$$

It is a simple model giving a good representation of the frequency behavior of the conductivity and permittivity of biological media, but it does not represent the physical phenomena at the origin of this behavior. It is used very frequently, notably by Gabriel.

Generally, the Cole Cole model allows a better representation of the measured values than the Debye model [47]. The universal dielectric response model represents the complex permittivity by a constant phase function of the form $(j\omega)^{n-1}$. The model combining the Debye and universal dielectric response models proposed by Raicu is of the type [50]-[55]:

$$\varepsilon_r = \varepsilon_{r\infty} - j\frac{\sigma}{\omega\varepsilon_0} + \frac{\Delta\varepsilon_{rn}}{\left((j\omega T)^{\alpha} + (j\omega T)^{1-\beta}\right)^{\gamma}} \tag{30}$$

Regardless of the model used, the different parameters are adjusted using optimization algorithms to correspond as precisely as possible to the values resulting from the measurements.

2.4. Interaction of RF Electromagnetic Waves with the Human Brain

To study the consequences of electromagnetic fields on living beings using Maxwell's equations, we can follow an approach based on the modeling of electromagnetic fields and their interaction with biological tissues [1] [2].

To do this we have a few steps that we must follow to carry out this modeling:

- Problem identification:
- Using Maxwell's equations:

The Maxwell equations to be implemented to model the coupling of electromagnetic fields-biological tissues are as follows [1]:

Maxwell-Gauss model expressing the electric field-biological tissue coupling:

$$\nabla \cdot \boldsymbol{E} = \frac{\rho}{\varepsilon_0} \tag{31}$$

Maxwell-Gauss model expressing the conservation of the magnetic field:

$$\nabla \cdot \boldsymbol{B} = 0 \tag{32}$$

Maxwell-Faraday model the unification between the electric field and the magnetic field:

$$\nabla \cdot \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{33}$$

Maxwell-Ampère model expressing the magnetic field-biological tissue coupling:

$$\nabla \cdot \boldsymbol{B} = \mu_0 \left(\boldsymbol{j} + \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} \right) \tag{34}$$

The absorbed power density D (W/m^3) in the biological environment transformed into heat is given by the following relation:

$$D = -\frac{\mathrm{d}P}{\mathrm{d}r} = \frac{\sigma^2}{2} E^2 \mathrm{e}^{-2\alpha r} \tag{35}$$

By introducing the density, we can also, from Equation (35), obtain the specific absorption rate (SAR) which is expressed in W/kg as follows [27]:

$$SAR = \frac{D}{\rho} = \frac{\sigma}{\rho} \cdot |E|^2 \tag{36}$$

2.5. The External Electric Field and the Internal Brain Current

The relationship between an external electric field applied to the head and internal brain currents is not a simple direct relationship but a complex interaction described by Ohm's law, requiring the brain to be modelled as a conducting medium whose properties depend on tissue geometry, tissue conductivity, and boundary conditions at the skull. The external electric field, applied to the scalp, induces an internal electric field in the brain. This induced electric field is then the cause of the internal conduction currents that circulate in the brain tissue.

Tissue Geometry Assumptions

Simplified Models: For simpler calculations, the brain can be modeled as a sphere or a series of concentric spheres, with each layer representing a different tissue (e.g., skull, cerebrospinal fluid, gray matter, white matter).

Realistic Models: More accurate models use magnetic resonance images (MRI) to segment the different brain regions and reconstruct their three-dimensional geometry.

Structural Complexity: The brain's geometry is very complex, with folds (gyrification) and varied structures, making it difficult to model perfectly.

Conductivity Assumptions

White Matter Anisotropy: White matter conductivity is generally higher along nerve fibers (conduction axis) than perpendicular to them, a phenomenon called anisotropy.

Isotropic Conductivities for Other Tissues: The conductivity of gray matter, cerebrospinal fluid, and the skull is often considered isotropic (identical in all directions) in simplified models.

Variable Conductivities: The conductivity of different brain tissues varies considerably, ranging from low values for the skull to higher values for gray matter and fluid.

Boundary Conditions

Dirichlet Conditions (*Imposed Potential*): The electrical potential at the skin surface (where the external field is applied) is often fixed to represent the source of the field.

Neumann Conditions (*Imposed Flux*): The external surface of the head (the scalp), the injected electric current can be specified. The absence of current through the skull (insulation) is also a common condition.

Interface conditions: The interfaces between different tissues (for example, between the skull and the cerebrospinal fluid), continuity of the electric field (or potential) and current flow is imposed, which is related to the continuity law of electromagnetism.

Non-reflection conditions: If the models are extended outside the head, conditions can also be imposed to avoid spurious reflections of the electromagnetic wave, representing the external field as a receding wave.

2.6. Modeling of Electrical Activity of the Brain under the Influence of the Electromagnetic Field

Under the influence of the electromagnetic field radiated by the GSM phone, the current induced by the latter is superimposed on the I_{induit} membrane stimulation current. For this purpose, the model proposed by Catherine Morris and Harold Lecar under this hypothesis can be written in the form (37):

$$\begin{cases} \dfrac{\mathrm{d}v(t)}{\mathrm{d}t} = \left(I_{stim} + I_{induit}\right) + G_L\left(V_L - v(t)\right) \\ \qquad\qquad + G_{Na}\left(v(t) + e(t)\right)\left(V_{Na} - v(t)\right) + N_K(t)\left[V_K - v(t)\right] \\ \dfrac{\mathrm{d}N_K(t)}{\mathrm{d}t} = G_K\left(v(t)\right) - g_K(t) \qquad (\mathrm{b}) \end{cases} \tag{37}$$

3. Results

Source of Model Parameters and Results

Considering experimental data of the brain biological tissue presented in the works of Benoit Perthame [6], the frequency range varying from 3.5 to 30 Gigas Hertz [Ghz] of propagation of 5G RF electromagnetic waves radiated by the GSM phone in the human brain and the interaction models proposed above (see equations from (1) to (37)), the results of the 2D simulations obtained are presented in **Figures 3-8**. **Figure 4(b)**, **Figure 7** and **Figure 8(b)** present the results obtained experimentally in the respective works of Benoit Perthame [6], (*In vitro* experiment by Rachid Behdad, 2016) [56] and (Rakotomananjara DF and Randriamitantsoa PA) [57].

4. Discussions

Considering the neuroscience theory based on the Morris-Lecar model, and typically considering the slowest channel and the electrical activity of muscle cells on the electromagnetic field and the modeling of cellular excitability as well as the influence on the cell concentration and mechanism of action of the electrical activity of the human brain, we can say that the electrical activity of the brain reflects a strong influence of the current that forms potential differences on the different points of the surface that can have consequences on the human brain (Maxwell's equations to visualize the effects of 5G RF electromagnetic waves).

Figure 3 represents the numerical resolution block of the Morris-Lecar Model. **Figure 4(a)** show the simulation results of the electrical activity of the brain without the influence of 5G RF with the choices of electrical parameters of the Morris-Lecar Model. The dynamics show a large excursion before returning close to the initial data. The brain excitation rhythm is periodic with a period of 9 seconds and an excitation frequency of 0.11 Hz. This result is close to the experiments presented in the work of (Benoit Perthame, 2023) [6] see **Figure 4(b)**.

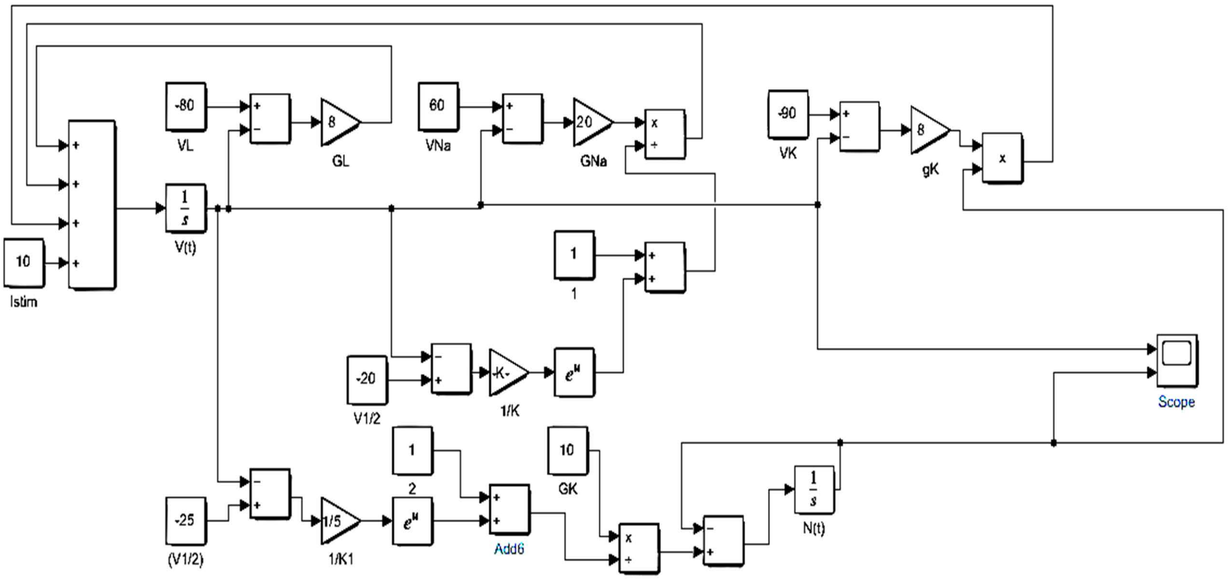
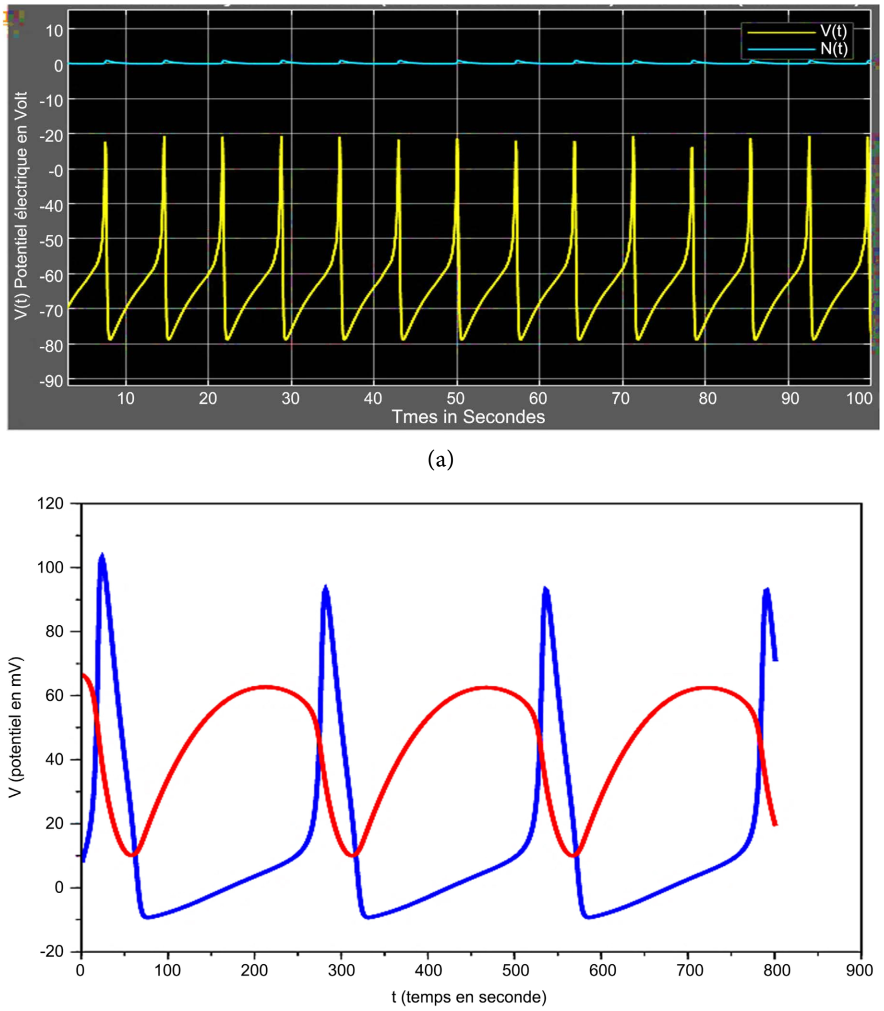


Figure 3. Brain rhythm simulation block (Morris-Lecar model) for an applied excitation current of 10 mA without influence of the current induced by the 5G RF electromagnetic field.



(a)

(b)

Figure 4. (a) Simulation result of brain electrical activity without influence of current induced by 5G RF electromagnetic field (Solution of Morris-Lecar system with choices of brain electrical parameters) and (b) Simulation result of brain electrical activity (Benoıt Perthame, 2023) [6].

Figure 5 shows the numerical resolution block of the Morris-Lecar model reproducing the electrical activity of the brain under the influence of 5G RF OEMs. However, **Figure 6** demonstrates the simulation result of the electrical activity of the brain under the influence of the 190 μA current induced by the 5G RF electromagnetic field. Under the action of OEMs, the brain rhythm can undergo periodic and excitation frequency changes; which can lead to a change in the state of consciousness, sleep cycle disruption, cognitive modulation, disruption of neuronal communication, brain plasticity, respiratory depression, sleep cycle disruption… if the membrane excitation period is reduced to 0.1 second, it leads to an increase in the membrane excitation frequency up to 10 Hz. These results confirm the in vitro experiments of Rachid Behdad [56], presented in **Figure 7(a)** and **Figure 7(b)**.

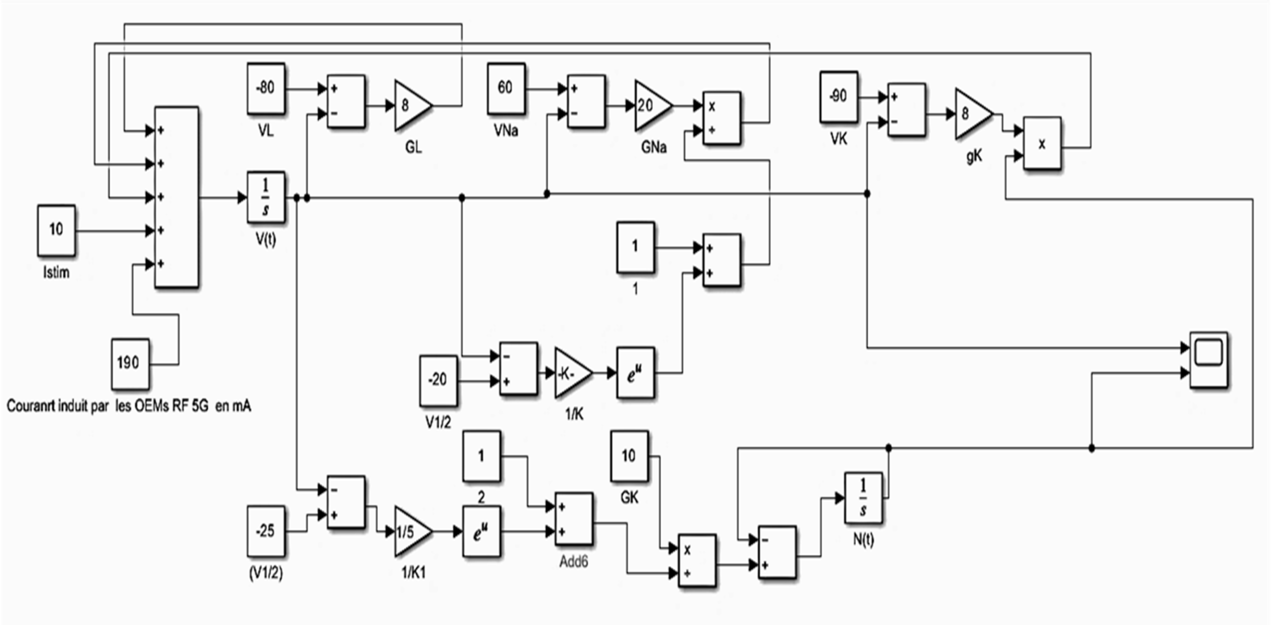


Figure 5. Brain rhythm simulation block (Morris-Lecar model) for an applied excitation current of 10 µA with influence of the 190 µA current induced by the 5G RF electromagnetic field.

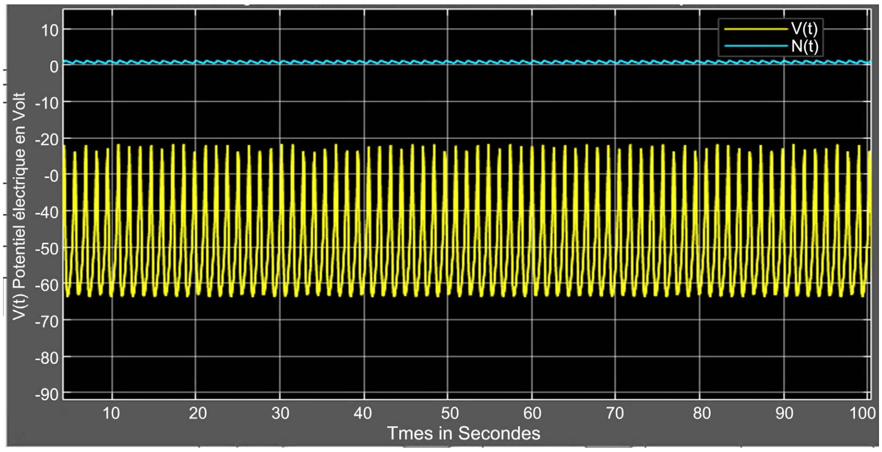
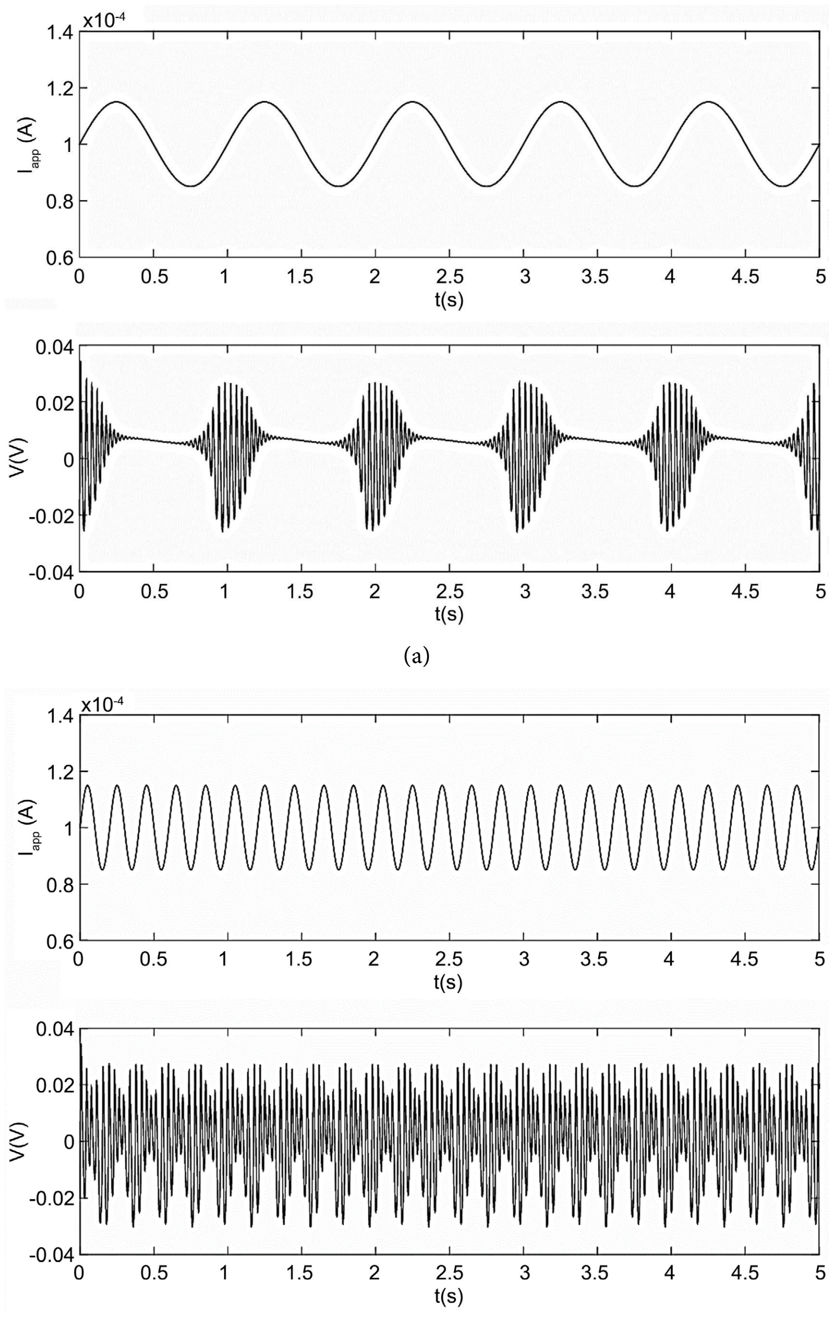


Figure 6. Simulation result of the electrical activity of the brain with the influence of the 190 mA current induced by the 5G RF electromagnetic field (Solution of the Morris-Lecar system with the choices of electrical parameters of the brain).

The curve in **Figure 8(a)** shows that the absorbed energy is a function of the conductivity of the biological medium and decreases in the direction of propagation. This is the quantification of the energy in a medium exposed to an electromagnetic field by evaluating the specific absorption rate (SAR) and attenuation in the skin, we see that very little energy is absorbed and most of it is absorbed in the epidermis (0.1 Cm). These results can be compared to those obtained experimentally in the work of (Rakotomananjara DP and Randriamitantsoa PA, 2020) [57], in **Figure 8(b)**. Electromagnetic waves can cause several harmful effects on living beings that several studies have confirmed. However, these effects are varied and depend on several parameters, including frequency, intensity and duration of exposure.



(a)

(b)

Figure 7. Influence of variation in neuron stimulation current on the electrical rhythm of the brain (*In vitro* experiment by Rachid Behdad, 2016) [56].

5. Conclusions and Perspectives

In this paper, we have chosen the modeling based on mathematical and numerical analysis on the analytical formalism of calculation of the electromagnetic field emitted by a dipole which takes into account, on the one hand, the physical phenomena of propagation of microwave electromagnetic plane wave and on the other hand the experimental values of 5G RF electromagnetic radiation emitted by the mobile phone in the spatiotemporal domain.

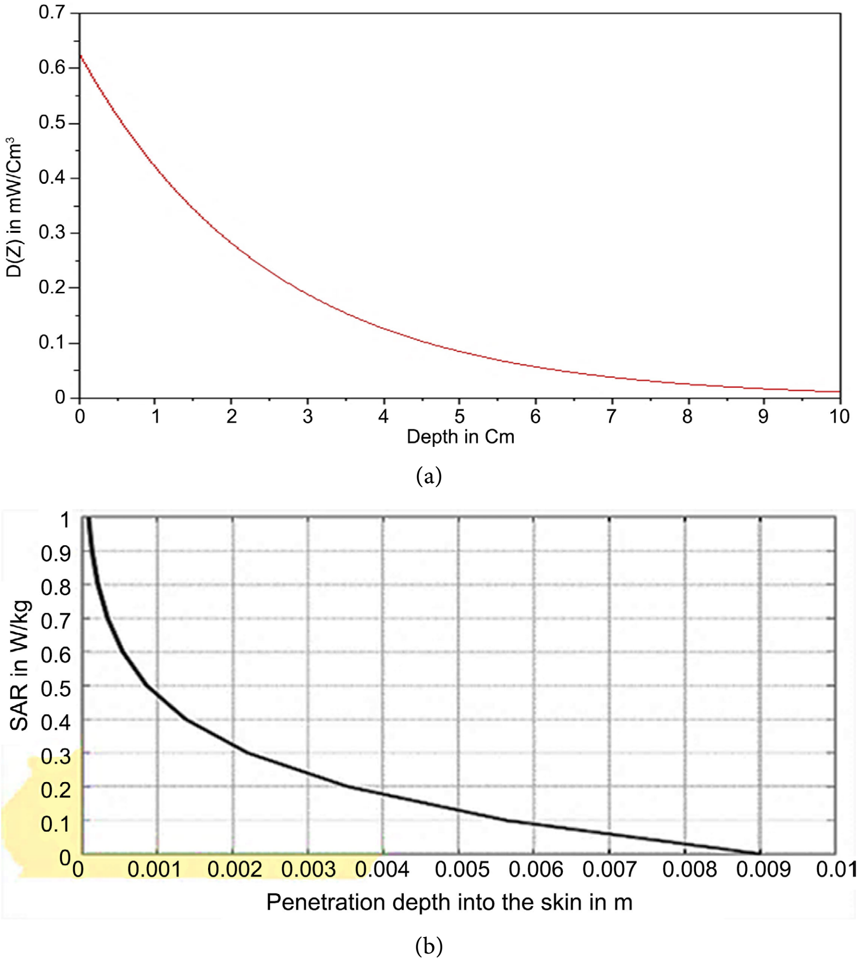


Figure 8. (a) Result of absorbed power density as a function of the thickness of the biological tissue. (b) Trend of SAR attenuation in the skin: result published by (Rakotomananjara DF and Randriamitantsoa PA from, 2020) [Research Laboratory in Telecommunications, Automatics, Signals and Images] [57].

5G brings an Energy Efficiency designed to be more energy efficient, which is crucial for battery-powered IoT devices, thus allowing a longer life and less maintenance. The integration of 5G with IoT has many benefits, but it also comes with potential risks and dangers that deserve to be considered, such as Data security, IoT device vulnerabilities, DDoS attacks, Interoperability issues, health risks, etc. For health, however, studies on the effects of 5G radio waves are still ongoing and some people remain concerned about the potential consequences, especially due to the increase in exposure to radio frequencies.

Although 5G and IoT offer incredible opportunities for connectivity and innovation, it is crucial to implement robust security measures and appropriate regulations to mitigate these potential risks.

The interactions of electromagnetic waves with the human brain are complex and dependent on several factors related to the characteristics of the incident wave, particularly in terms of thermal and non-thermal effects, although these effects have a considerable impact on sleep, and we implemented the Morris-Lecar model as a basis for evaluating the modification of brain electrical activity to obtain consistent results.

The simulation result obtained in this article is similar to the model experiments presented in the works of (Benoıt Perthame) [6] and Rakotomananjara DP and Randriamitantsoa PA [57]. These results show that under the influence of 5G RF OEMs, the electrical activity of the brain (although these results are still preliminary and require investigation), these waves can bring changes that can lead to biological consequences related to imbalances in different mental states (attention, relaxation, sleep, etc.), to the disruption of neuronal communication, affecting cognitive functions, memory and concentration. Added to this is the oxidative stress that can affect the functionality of brain membranes, the alteration of cerebral blood circulation as well as the change in neurotransmission that can influence cognition and mood, since 5G waves operate at higher frequencies than previous generations of mobile technology and this raises questions with biological tissues and the brain, because they have direct influences on electroencephalography. Therefore, we considered it useful that the modeling of a human biological tissue analyzed from Maxwell's equations and the Morris-Lecar model is more suitable for the study of a system as complicated and disparate as a complex of biological tissues.

A direct perspective of this study is the application of one of the methods we used for the simulation of the 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 scope of the biological tissues discussed in this article. The complete modeling of the brain, heart, faith and simulation constitutes a much broader perspective and can also be comprehensively analyzed from the MoM method.

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Conflicts of Interest

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

References

[1] Nzao, A.B.S. (2021) Study and Modeling of Human Biological Tissue Exposed to High Frequency Electromagnetic Waves. *Open Journal of Applied Sciences*, **11**, 1109-1121. https://doi.org/10.4236/ojapps.2021.1110083

[2] Staebler, P. (2017) Human Exposure to Electromagnetic Fields. Wiley.

[3] Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) (2007) Possible Effects of Electromagnetic Fields (EMF) on Human l'Internet Health. European Commission.

[4] Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) (2015) Potential Health Effects of Exposure to Electromagnetic Fields (EMF). European Commission.

[5] World Health Organization (WHO) (1993) Electromagnetic Fields (300 Hz to 300 GHz), Environmental Health Criteria 137. WHO.

[6] Benoit Perthame (2023) Mathematical Models in Neuroscience. Pierre and Marie Curie University-Paris 6, CNRS UMR 7598, J.-L. Lions Laboratory.

[7] Bressloff, P.C. (2014) Waves in Neural Media, Lecture Notes on Mathematical Modelling in the Life Sciences. Springer.

[8] Gerstner, W. and Kistler, W.M. (2002) Spiking Neuron Models. Cambridge University Press. https://doi.org/10.1017/cbo9780511815706

[9] Goodwin, B.C. (1965) Oscillatory Behavior in Enzymatic Control Processes. *Advances in Enzyme Regulation*, **3**, 425-437. https://doi.org/10.1016/0065-2571(65)90067-1

[10] Hirsch, M.W., Smale, S. and Devaney, R.L. (2013) Discrete Dynamical Systems. In: *Differential Equations*, *Dynamical Systems*, *and an Introduction to Chaos*, Elsevier, 329-359. https://doi.org/10.1016/b978-0-12-382010-5.00015-4

[11] Izhikevich, E.M. (2007) Dynamical Systems in Neuroscience: The Geometry of Excitability and Bursting. The MIT Press. https://doi.org/10.7551/mitpress/2526.001.0001

[12] Kuramoto, Y. (1975) Self-Entrainment of a Population of Coupled Non-Linear Oscillators. In: Araki, H., Ed., *Lecture Notes in Physics*, Springer-Verlag, 420-422. https://doi.org/10.1007/bfb0013365

[13] Murray, J.D. (2002) Mathematical Biology. Springer.

[14] Strogatz, S.H. (1994) Nonlinear Dynamics and Chaos. Addison-Wesley.

[15] Terman, D. (2014) Mathematical Neuroscience. *The American Mathematical Monthly*, **121**, 824-839. https://doi.org/10.4169/amer.math.monthly.121.09.824

[16] Winfree, A.T. (1967) Biological Rhythms and the Behavior of Populations of Coupled Oscillators. *Journal of Theoretical Biology*, **16**, 15-42. https://doi.org/10.1016/0022-5193(67)90051-3

[17] Catteral, W.A. (2011) Voltage-Gated Calcium Channels. University of Washington.

[18] Ruiz, M.L. and Kraus, R.L. (2015) Voltage-Gated Sodium Channels: Structure, Function, Pharmacology, and Clinical Indications. *Journal of Medicinal Chemistry*, **58**,

7093-7118.

[19] Nzao, A.B.S. (2024) Study of the Simulation and Application of the PEEC Method for Modeling the Prediction of Emissions Radiated by the Onboard Electronic Wiring System. *Computer and Information Science*, **17**, 7-27. http://madarevues.recherches.gov.mg/IMG/pdf/art_no11_2020_vol_2_pp_110-127_modelisation_des_mecanismes_des_interactions_des_rayonnements_electro-magnetiques_avec_les_et.pdf

[20] Amadou, B.D. (2023) Co-Simulation for EMC Modeling of Complex Electrical Systems. Ph.D Thesis, University of Lyon.

[21] Nzao, A.B.S. (2022) Analysis and FDTD Modeling of the Influences of Microwave Electromagnetic Waves on Human Biological Systems. *Open Journal of Applied Sciences*, **12**, 912-929. https://doi.org/10.4236/ojapps.2022.126063

[22] Moureaux, P. (2018) Exposure to Electromagnetic Fields. INRS. http://www.rst-sante-travail.fr/rst/dms/dmt/ArticleDMT/PratiquesProfessions/TI-RST-TM-44/tm44.pdf

[23] Conil, E. (2005) Electromagnetism in Complex Environments: From the Near Field to the Far Field. Doctoral Thesis, National Polytechnic Institute of Grenoble.

[24] Tomenius, L. (1986) 50-hz Electromagnetic Environment and the Incidence of Childhood Tumors in Stockholm County. *Bioelectromagnetics*, **7**, 191-207. https://doi.org/10.1002/bem.2250070209

[25] Savitz, D.A., Wachtel, H., Barnes, F.A., John, E.M. and Tvrdik, J.G. (1988) Case-Control Study of Childhood Cancer and Exposure to 60-Hz Magnetic Fields. *American Journal of Epidemiology*, **128**, 21-38. https://doi.org/10.1093/oxfordjournals.aje.a114943

[26] Jossinet, J. (1998) The Impedivity of Freshly Excised Human Breast Tissue. *Physiological Measurement*, **19**, 61-75. https://doi.org/10.1088/0967-3334/19/1/006

[27] 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

[28] Camp, J.T., Jing, Y., Zhuang, J., Kolb, J.F., Beebe, S.J., Song, J., *et al.* (2012) Cell Death Induced by Subnanosecond Pulsed Electric Fields at Elevated Temperatures. *IEEE Transactions on Plasma Science*, **40**, 2334-2347. https://doi.org/10.1109/tps.2012.2208202

[29] Wtorek, J., Bujnowski, A., Poliński, A., Józefiak, L. and Truyen, B. (2004) A Probe for Immittance Spectroscopy Based on the Parallel Electrode Technique. *Physiological Measurement*, **25**, 1249-1260. https://doi.org/10.1088/0967-3334/25/5/014

[30] Scorretti, R. (2003) Numerical and Experimental Characterization of the LF Magnetic Field Generated by Electrotechnical Systems with a View to Modeling the Currents Induced in the Human Body. PhD Thesis, Lyon Central School.

[31] Purschke, M., Laubach, H., Rox Anderson, R. and Manstein, D. (2010) Thermal Injury Causes DNA Damage and Lethality in Unheated Surrounding Cells: Active Thermal Bystander Effect. *Journal of Investigative Dermatology*, **130**, 86-92. https://doi.org/10.1038/jid.2009.205

[32] Fear, E.C. and Stuchly, M.A. (1998) Modeling Assemblies of Biological Cells Exposed to Electric Fields. *IEEE Transactions on Biomedical Engineering*, **45**, 1259-1271. https://doi.org/10.1109/10.720204

[33] Scharfetter, H. (1999) Structural Modeling for Non-Invasive Impedance-Based Diagnostic Methods. Habilitation Thesis, Technical University of Graz.

[34] Jaspard, F. and Nadi, M. (2002) Dielectric Properties of Blood: An Investigation of Temperature Dependence. *Physiological Measurement*, **23**, 547-554. https://doi.org/10.1088/0967-3334/23/3/306

[35] TB Carlos Konlack and Roger TCHUIDJAN (2011) Analysis of the Impact of Electromagnetic Waves on Humans. http://www.afriquescience.info

[36] Cocquerelle, J.-L. (1999) CEM and Power Electronics. Edition Technip.

[37] Degauque, P. and Hamelin, J. (1990) Electromagnetic Compatibility: Radioelectric Noise and Disturbances. Technical and Scientific Collection of Telecommunications, Edition Dunod.

[38] Zangui, S. (2011) Determination and Modeling of Magnetic Near-Field Coupling between Complex Systems. Doctoral Thesis, Ecole Centrale de Lyon.

[39] Ikhlef, N. (2002) Electromagnetic Radiation of the Energy Transport Network: Coupling with Wire Structures, Reduction of the Magnetic Field. Master's Thesis, CU of Jijel.

[40] Manel, B. (2017) CEM Electromagnetic Compatibility and Energy Networks, Disturbances, Effects and Solutions. Thesis, University of the Mentouri brothers of Constantine.

[41] Bernard, L. (2007) Electrical Characterization of Biological Tissues and Calculation of the Phenomena Induced in the Human Body by Electromagnetic Fields with a Frequency below GHz. Thesis, Central School of Lyon.

[42] Haddar, D., Haacke, E.M., Sehgal, V., Delproposto, Z., Salamon, G., Seror, O., *et al.* (2004) L'imagerie de susceptibilité magnétique: Théorie et applications. *Journal de Radiologie*, **85**, 1901-1908. https://doi.org/10.1016/s0221-0363(04)97759-1

[43] Schumann, D. (1978) Electrical Properties of Charged Interfaces. Masson.

[44] Zoltowski, P. (1998) On the Electrical Capacitance of Interfaces Exhibiting Constant Phase Element Behaviour. *Journal of Electroanalytical Chemistry*, **443**, 149-154. https://doi.org/10.1016/s0022-0728(97)00490-7

[45] Grimnes, S. and Martinsen, Ø.G. (2000) History of Bioimpedance and Bioelectricity. In: *Bioimpedance and Bioelectricity Basics*, Elsevier, 313-319. https://doi.org/10.1016/b978-012303260-7/50009-5

[46] Martinsen, O.G., Grimnes, S. and Schwan, H.P. (2002) Interface Phenomena and Dielectric Properties of Biological Tissue. In: *Encyclopedia of Surface and Colloid Science*, Marcel Dekker, Inc., New York, 2643-2652.

[47] Simicevic, N. and Haynie, D.T. (2005) FDTD Simulation of Exposure of Biological Material to Electromagnetic Nanopulses. *Physics in Medicine and Biology*, **50**, 347-360. https://doi.org/10.1088/0031-9155/50/2/012

[48] El-Lakkani, A. (2001) Dielectric Response of Some Biological Tissues. *Bioelectromagnetics*, **22**, 272-279. https://doi.org/10.1002/bem.50

[49] Tamura, T., Tenhunen, M., Lahtinen, T., Repo, T. and Schwan, H.P. (1994) Modelling of the Dielectric Properties of Normal and Irradiated Skin. *Physics in Medicine and Biology*, **39**, 927-936. https://doi.org/10.1088/0031-9155/39/6/001

[50] Raicu, V. (1999) Dielectric Dispersion of Biological Matter: Model Combining Debye-Type and "Universal" Responses. *Physical Review E*, **60**, 4677-4680. https://doi.org/10.1103/physreve.60.4677

[51] Raicu, V., Kitagawa, N. and Irimajiri, A. (1999) A Quantitative Approach to the Dielectric Properties of the Skin. *Physics in Medicine and Biology*, **45**, L1-L4. https://doi.org/10.1088/0031-9155/45/2/101

[52] Coperich, K.M., Ruehli, A.E. and Cangellaris, A. (2000) Enhanced Skin Effect for Partial-Element Equivalent-Circuit (PEEC) Models. *IEEE Transactions on Microwave Theory and Techniques*, **48**, 1435-1442. https://doi.org/10.1109/22.868992

[53] Yahyaoui, W. (2012) Characterization and Modeling of Emissions Radiated by the Wiring of On-Board Electronic Systems. Doctoral Thesis, Universite de Paris-Sud XI. https://theses.hal.science/tel-00737499/document

[54] Dubois, T. (2009) Study of the Effect of Electromagnetic Waves on the Operation of Electronic Circuits—Implementation of a Method for Testing Electronic Systems. Montpellier II Science and Technology University of Languedoc.

[55] Jaspard, F. and Nadi, M. (2002) Dielectric Properties of Blood: An Investigation of Temperature Dependence. *Physiological Measurement*, **23**, 547-554. https://doi.org/10.1088/0967-3334/23/3/306

[56] Rachid Behdad. (2016) Experimental study of Morris-Lecar Neurons: Implementation, Coupling, and Interpretation. Thesis, University of Burgundy. https://theses.hal.science/tel-01257832/

[57] Rakotomananjara and Randriamitantsoa (2020) Modeling the Mechanisms of Interaction of Electromagnetic Radiation with Living Beings. http://madarevues.recherches.gov.mg/IMG/pdf/art_no11_2020_vol_2_pp_110-127_modelisation_des_mecanismes_des_interactions_des_rayonnements_electro-magnetiques_avec_les_et.pdf