RF-Field and Microwave Interaction with Biological Systems

1) INTRODUCTION

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

For several decades, electromagnetic has been used to detect bioelectric and biomagnetic activities of different organs. Some of the most important instrumentations to measure biosignals include: electrocardiogram (ECG) to reconstruct “potentials on the epicardial surface of the heart”, electro-encephalogram (EEG) to record “electrical activity of the outer layers of the brain”, and electromyogram (EMG) to detect the “activity of skeletal muscle” [1]. The frequency component of all these devices is up to about few kHz, which falls into low-frequency range of the electromagnetic (EM)
spectrum. The energy of EM waves is quantified with the quantum of energy, which is proportional to the frequency \( W=hf \), where \( f \) is the frequency and \( h \) is Plank’s constant. For instance, the energy of one quantum of energy is about \( 10^{12} \) times greater if the frequency increases from \( 10^8 \) Hz to \( 10^{20} \) Hz (ionizing X-rays) [2]. Ionization potential is “the energy required to remove one electron from the highest energy orbit, and it is typically “of the order of \( 10 \) eV” [3]. In this review, we study the interaction of RF fields and microwaves with biological systems, where the quantum energies are well below the ionization potentials. Nevertheless, there are other possible biological effects, such as “heating, dielectrophoresis, and depolarization of cell membranes” [3], which can take place at these lower frequencies and have to be taken into account. For instance, a very low frequency EM field applied at the “membrane’s outer surface” could potentially alter ligand-receptor interactions, changing the state of large membrane molecules that regulate the cell’s internal processes [4].

II) FUNDAMENTALS

a. Dielectric Properties and Relaxation Theory

The interaction between electric point charges can be described by Coulomb’s law [5]:

\[
F = \frac{q_1 q_2}{4\pi \varepsilon_0 r^2} \quad (N)
\]

where \( F \) is the force (in Newton, N) created by \( q_1 \) and exerted onto \( q_2 \), \( q_1 \) and \( q_2 \) are the value of the charges expressed in coulombs (C), \( r \) is the distance between them (m), and \( \varepsilon_0 \) is the permittivity of free space (\( 8.854 \times 10^{-12} \) Fm\(^{-1} \)). The intensity of the electric field \( (E) \) of force created by the charge \( q_1 \) on \( q_2 \) is then defined as [5]:

\[
E = \frac{F}{q_2} = \frac{q_1}{4\pi \varepsilon_0 r^2} \quad (Vm^{-1})
\]
As shown in Figure 1(a), when a polar molecule is submitted to an applied electric field \( E \), it undergoes a force \( F \), which is proportional to \( E \). The exerted force \( F \) polarizes the molecule; “the amount of which is called the polarization vector \( P \)” [3]. Dipolar polarization is a result of the “alignment of the molecule dipolar moment due the applied electric field” [3] (Figure 1(b)).

![Figure 1: Polar molecule submitted to an applied electric field (E), (a) before and (b) after dipolar polarization.](image)

When the electric field is discontinued, the excitation of polar molecules is ceased and “the system relaxes to a new equilibrium”. This relaxation process in the time domain can be described by relaxation time constant \( \tau \), which in biological systems can range from a picosecond to several seconds depending on the applied electric field and the dielectric properties of the material [3].

If a material is placed in a parallel-plate capacitor characterized by capacitance \( C \) and conductance \( G \), a step voltage at time \( t=0 \) can excite the material, resulting in a single relaxation process with relaxation time constant \( \tau \). In this simplified case, the surface charge density \( D \) on the capacitor plates can be calculated using Debye relaxation model given by:

\[
D = D_\infty + (D_0 - D_\infty)(1 - e^{-t/\tau})
\]  

(3)
where \( D_\infty \) is “the surface charge density after the step voltage \((t=0^+)\)” and \( D_0 \) is “the charge density long after the step voltage, when a system has obtained a new equilibrium” [6].

The response of this system in a frequency domain is represented by relative permittivity \( \varepsilon_r^* \), also known as complex permittivity, and can be obtained by applying Laplace transform [7]

\[
\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r'' = \varepsilon_r\infty + \frac{\varepsilon_r0 - \varepsilon_r\infty}{1 + j\omega\tau}
\]  

(4)

where \( \omega \) is the angular frequency of the electric field, \( \varepsilon_0 \) is the permittivity at low frequency (where the polarization is fully manifested) and \( \varepsilon_\infty \) is the permittivity at high frequency (where the polar particles are not able to respond to the applied electric field). The parameter \( \varepsilon_\infty \) is often called “optical dielectric constant”, which is the value at optical frequencies [3].

The real part of the complex permittivity is called dielectric constant, also known as relative static permittivity, or just relative permittivity (dielectric constant is sometimes called relative permittivity and one should be careful and distinguish if it refers to the relative permittivity as a complex value or just it’s real part).

\[
\varepsilon_r' = \varepsilon_r\infty + \frac{\varepsilon_r0 - \varepsilon_r\infty}{1 + (\omega\tau)^2}
\]  

(5)

Permittivity of a material, which describes its ability to polarize in response to an electric field, can be obtained by multiplying the relative static permittivity \( \varepsilon_r \) by the permittivity of free space \( \varepsilon_0 \):

\[
\varepsilon = \varepsilon_r'\varepsilon_0
\]  

(6)
The imaginary part of the complex permittivity, known as *dielectric loss*, “reflects the losses associated with the movement of charges in phase with the electric field”, and is given by [3]:

\[
\varepsilon'' = \frac{\sigma}{\omega \varepsilon_0} = \frac{(\varepsilon_{r0} - \varepsilon_{r\infty}) \omega \tau}{1 + (\omega \tau)^2}
\]

where \( \sigma \) is the conductivity. Dielectric properties of biological systems are commonly represented by relative permittivity (dielectric constant) and conductivity.

The *characteristic relaxation frequency* \( f_c \) (also known as *critical frequency*) corresponds to the maximum value of the dielectric loss factor \( \varepsilon'' \) (\( \omega \tau = 1 \)) and is given by [3]:

\[
f_c = \frac{1}{2 \pi \tau}
\]

Figure 2 illustrates the typical behavior of the real and imaginary parts of the complex permittivity as a function of angular frequency \( \omega \). It can be seen that the imaginary part is zero only when the real part is frequency independent (at \( \omega = 0 \) and \( \omega = \infty \)). In addition, the critical frequency is reached when the dielectric constant variation with respect to the frequency is maximum (steepest slope of \( \varepsilon_r \) curve).
The real and imaginary parts of the complex permittivity can be calculated from each other over the whole frequency range by the Kramer and Kronig formulas [8]:

\[
\varepsilon'(\omega) = \varepsilon_0 + \frac{2}{\pi} \int_0^\infty \frac{x \varepsilon''(x)}{x^2 - \omega^2} dx \\
\varepsilon''(\omega) = -\frac{2\omega}{\pi} \int_0^\infty \frac{\varepsilon'(x) - \varepsilon_\infty}{x^2 - \omega^2} dx
\]

(9)

Moreover, Maxwell’s equations show that permittivity and conductivity of materials are not independent of each other and with increasing frequency, if the permittivity decreases, the conductivity will increase. This relation can be explained by the conservation of energy of the electric field, which can be either stored or dissipated through the material the field is interacting with. Stored energy is reflected in the real part of the complex permittivity (dielectric constant), while the imaginary part measures the dielectric losses [3].

Figure 2 shows one classical representation of complex permittivity by plotting its real and imaginary parts as a function of frequency. The **Cole-Cole plot** is an alternative representation of \( \varepsilon_r^*(\omega) \) in its complex plane, i.e. to plot the imaginary part for a certain frequency \( \varepsilon''(\omega) \) against the real part at the same frequency, \( \varepsilon'(\omega) \), as illustrated in Figure 3. It can be shown that the real and imaginary parts of the complex permittivity are related to each other through the equation of a circle in the complex plane \( \varepsilon_r^*(\omega) \) [9]:

\[
\left[ \varepsilon'(\omega) - \frac{1}{2} (\varepsilon_0 + \varepsilon_\infty) \right]^2 + \left[ \varepsilon''(\omega) \right]^2 = \frac{1}{4} (\varepsilon_0 - \varepsilon_\infty)^2
\]

(10)

The Cole-Cole plot is useful way to find out “whether a system has a single relaxation time” or not [3]. Each point of the semicircle corresponds to a given frequency \( \omega \), and the summit indicates the characteristic relaxation frequency \( f_c \), where \( \omega \tau = 1 \).
b. Multiple Relaxation

Unlike in the simplified case described in the previous section, biological systems are characterized by multiple relaxation processes, which in turn correspond to multiple charge densities $D_1, D_2, \ldots$ and multiple relaxation time constants, $\tau_1, \tau_2, \ldots$ As a result of this phenomenon, the surface charge density ($D$) in equation (3) is now given by [6]:

$$D = D_\infty + D_1 (1 - e^{-t/\tau_1}) + D_2 (1 - e^{-t/\tau_2}) + \ldots$$

(11)

and the complex permittivity in (4) can be redefined as [10]:

$$\varepsilon_r^* = \varepsilon_r(\infty) + \frac{\varepsilon_r(0) - \varepsilon_r(\infty)}{1 + (j\omega\tau)^{1-\alpha}}$$

(12)

where $\alpha$ is an experimental parameter [11], ranging from 0.3 to 0.6 for most biological materials [12,13]. Obviously, if $\alpha=0$, equations (4) and (12) would be identical. Since in biological systems $\alpha > 0$, the center of corresponding Cole-Cole semicircle is shifted down, as shown in Figure 4 [3].
c. Measuring of EM Penetration in Biological Tissues: Skin Depth

In good conductors, the density of free charges is negligible and the conduction current is large with respect to the displacement current and is proportional to the electric field. The propagation of electromagnetic waves inside good conductors is governed by the diffusion equation, where “the amplitude of the electric fields decays exponentially” as the waves travel inside the material. The decay parameter $\delta$ is called skin depth and is defined as [3]:

$$\delta = \frac{1}{\sqrt{(\omega \mu \sigma / 2)}} \ (m)$$

where $\mu$ is the permeability of the material. Skin depth is the distance inside the material where the electric field reduces to approximately 37% of its value at the interface [3]. From equation (13), skin depth is inversely proportional to the permeability and conductivity of the material, and also to the angular frequency of the penetrating waves.

However, biological materials are not good conductors, and because of their significant losses, they are not considered lossless. As a result, the displacement and conduction currents in these materials are of the same order over a wide frequency range, and the skin depth expression in equation (13) should be substituted with [14]:
\[ \delta = \frac{1}{\omega} \sqrt{\left(\frac{\mu \varepsilon}{\omega}\right)} \left[ (1 + p^2)^2 - 1 \right] \quad (m) \quad (14) \]

where \( p = \frac{\sigma}{\omega \varepsilon} \) is the ratio of the conduction to the displacement current. For large values of \( p \), equation (14) approaches to (13). Skin depth expression describes the *skin effect*: The concentration of electric fields, currents, and charges is higher near the surface of the material in which the waves are penetrating, and it decreases exponentially as the waves travel further into the material. For instance, at a depth of \( 3\delta \), the amplitude of the electric field reduces to 5% of its value at the interface and the corresponding power is only 0.25%. These values decrease to 1% and 0.01% respectively, as the depth increases to \( 5\delta \) [3]. Figure 5 shows the relative absorbed power in human muscles “as a function of penetration depth” at several frequencies ranging from 10 MHz to 2.4 GHz [3].

![Figure 5: Relative power absorbed in human muscles as a function of skin depth at frequencies: 10, 27.12, 40.68, 100, 433, 915, and 2450 MHz [3].](image)
III) DIELECTRIC CHARACTERIZATION IN TISSUE

a. RF/Microwave Interaction

Radiofrequency EM waves and microwaves can interact with biological tissue through either thermal or non-thermal mechanisms, and resulting biological effects depend upon a number of factors, including EM field strength, frequency, waveforms, modulation, and duration of exposure [15,16]. As the RF/microwave electric field generates an A.C. current, the EM energy is rapidly transferred into tissue molecules, resulting in ion acceleration and collision with other molecules. Consequently, local temperature increases and this will ultimately lead to an increase in tissue temperature. Water molecules also contribute to tissue temperature rise. Because of their large permanent dipole moment and the viscosity of water, the electric field has to do work to rotate the dipoles, which results in “energy transfer into the liquid-heat” [17]. On the other hand, non-thermal mechanisms are not directly associated with the temperature change, but rather produce various types of structural transformations and molecular alterations.

Non-thermal effects of RF and microwave irradiation have been studied over last decades, and several electric and magnetic effects associated with non-thermal mechanisms have been reported. One of the most important effects is the “protein conformational change” [17]. Proteins consist of amino acid chain(s), whose arrangement in space is called conformation. The efficiency of the protein as an enzyme is tightly linked to its conformation. Since side chains of amino acids are often polar and have dipole moment, RF/microwave irradiation can polarize them and cause changes in protein conformation. These changes mainly depend on the amplitudes of the excitation and duration of the exposure [17]. RF and microwave irradiation can also affect cell receptors.
through binding of light ligands such as Ca$^{2+}$ to a protein. In such case, altering the protein conformation may disturb cell receptor function [4]. Other non-thermal effects reported in different studies include: enhanced attraction between cells due to the RF electric field [18], changes in cellular growth rate and properties (ranging from 29% decreasing to 15% increasing of growth rate of yeast at $\sim$ 42 GHz) [19], interference with repair mechanism and even gene mutation in bacteria at 65-75 GHz [20], and higher concentration of free-radicals in low intensity RF fields (< 80 MHz) [21].

Thermal effects of RF/microwave interaction with biological tissues are reasonably well understood and it is generally accepted that the temperature rises that result from exposures below guideline levels are safe and far from causing adverse health issues [17]. However, the position is less clear for non-thermal effects. There are still a lot of debates around possible non-thermal effects on physiological behavior of living organisms, and more research needs to be done in this area.

The SAR (Specific Absorption Rate by the body for frequencies between 100 kHz and 6 GHz [22]) threshold is commonly used as the basis of the standard. According to the international Committee on Electromagnetic Safety (ICES), the average SAR of 4 W/kg over a whole-body is considered the threshold below which adverse effects are not expected. However, in order to ensure a safety margin, the official SAR threshold is 0.4 W/kg for occupational exposure and 0.08 W/kg for public exposures [23].

**b. Dielectric Dispersion in Biological Tissues**

It was shown in Figure 2 that the imaginary part of the complex permittivity exists only if the real part (dielectric constant) is frequency dependent. When dielectric property of a material, such as permittivity and conductivity, vary as a function of frequency, the
material is called dispersive. In biological materials, dielectric constant decreases with increasing frequency, while conductivity increases. This is due to the fact that different electrical charges are not able to follow the changes in the applied electric field. Figure 6 shows how the dielectric constant of muscle tissue varies as a function of frequency [3]. Very similar behavior is observed in other biological tissues, where there are three major drops in dielectric constant, named alpha, beta, and gamma dispersions.

![Figure 6: Dielectric constant of living material (muscle) as a function of frequency](image)

**Alpha dispersion:** $\alpha$ dispersion has a characteristic frequency in mHz – kHz range, where relative permittivity (dielectric constant) attains values as large as $10^6 - 10^7$, largely due to the counterion polarization effects:

Ionic diffusion in the “electrical double layers” next to charged particles results in counterion effect [3]. Counterion layer is a thin sheet of ions around a particle containing only ions with “opposite sign of that of the fixed charge on the particle” [3]. The counterions and ions of the same sign in the bulk electrolyte can exchange freely, whereas those of opposite sign are excluded from the counterion layer. Therefore, motion of ions in the bulk electrolyte is determined by whether their signs are the same or
opposite of the ions in the counterion layer. Those of the same sign can enter the counterion layer and their charge is quickly conducted to the opposite side of the particle. On the other hand, ions of opposite sign travel in the bulk electrolyte surrounding the particle. As a result, a large dipole moment is induced in the system, and the permittivity (ability of a material to polarize) increases. Counterion effects significantly contribute to $\alpha$ dispersion in tissue at low frequencies [2,3].

There are other effects contributing to the alpha dispersion, including: “active membrane conductance”, “charging of intracellular structures” connected to the outer cell membrane, and possibly frequency dependence in the membrane impedance [3,24]. Despite its significant change in relative permittivity, alpha dispersion does not appear in conductivity. In fact, the total increase in conductivity associated with $\alpha$ dispersion is only about 0.005 Sm$^{-1}$. At low frequencies, cells are poorly conductive comparing to the surrounding electrolyte, and the conductivity depends on the “volume fraction of extracellular fluid”, the only place where current can flow. Hence, biological tissues are generally resistive at these frequencies [12].

**Beta dispersion:** $\beta$ dispersion occurs in RFs, ranging from 0.1 to about 100 MHz. “Capacitive charging of cellular membranes” in tissues, and dipolar orientation of tissue proteins at high radio frequencies are the primary and secondary causes of beta dispersion [3]. The corresponding increase in conductivity values is about 2 orders of magnitude larger (0.4 Sm$^{-1}$) than that in alpha dispersion, mainly because the cell membranes at these frequencies are mainly shorted out and do not resist to current flow [3]. Nonetheless, conductivity increase is still insignificant,
**Gamma dispersion**: γ dispersion arises at microwave frequencies, ranging from 0.1 to about 100 GHz. It is primarily due to dipolar relaxation of water, which undergoes nearly single relaxation process, with center frequency at about 25 GHz at body temperature (pure water). Water associated with protein surface has a lower relaxation frequency (close to 1 GHz) than that of the bulk liquid. Since water accounts for a major part of most biological tissues (~80 in soft tissues), dielectric properties of tissues at microwave frequencies reflect those of water. At these frequencies, conductivity of the tissue increases significantly (~ 70 Sm$^{-1}$), mainly due to the dielectric relaxation of water [7,12].

c. Influence of Temperature and Water Content in Dielectric Properties

Any temperature changes directly affect the conductivity of biological materials. The critical frequency $f_c$ increases with temperature at a rate of about 2 percent per °C, for all dispersions [25]. For large temperature increases (above 44.5 °C), the dielectric properties of the tissue undergo sudden and irreversible changes, which reflects the “thermal effect of EM interaction” [3]. At RF/microwaves, conductivity of the tissue electrolyte determines that of the tissue, and both ionic conductivity and relaxation frequency increases as the temperature rises. On the contrary, at these frequencies, the relative static permittivity (dielectric constant) varies insignificantly with temperature [3].

Dielectric properties of tissues vary as a function of the water content. Numerous research groups have studied this correlation over last decades. Figure 7 shows the dielectric properties of the various low-water-content tissues as a function of water content. In (a), tissue permittivity is normalized by the permittivity of water, and in (b) conductivity is plotted against volume fraction of tissue water at 25°C [25]. The data represent single measurements, or averages of repeated measurements on different areas.
of the same tissue sample, where each bar indicates the range of obtained values. Sample tissues were bone marrow (O) and fat (+), and the curve represents predicted values based on the “Maxwell mixture formula” [26]. The tumor and normal tissue data (×) from [27] are also added to these plots for comparison purposes. Further details can be found in [25]. It can be concluded from Figure 7 that higher water-content tissues exhibit higher permittivity (dielectric constant) and conductivity values. Similar results have been obtained over all RF and microwave frequency ranges, suggesting a direct relationship between dielectric properties of tissues and their water content.

Figure 7: Dielectric properties of various tissues as a function of water content [25]
d. Dielectric Properties of Different Biological Tissues

In this section, dielectric properties of several tissues over ELF/RF/microwave frequency ranges are reviewed. Table 1 [25] shows (a) dielectric constant and (b) conductivity of several body tissues at body temperature over microwave frequencies, ranging from 25 MHz to 8.5 GHz. At a given frequency, high-water-content tissues, such as muscle, liver, spleen, and kidney exhibit significantly higher dielectric properties (both dielectric constant and conductivity) comparing to low-water-content tissues, such as fat and bone marrow. More specifically, at for example 50 MHz or 1 GHz, dielectric constants and conductivity values of liver are roughly 10 times higher than those of bone marrow (red lines in Table 1), as expected from section (III-c). We can also verify $\beta$ and $\gamma$ dispersion in Table 1: In GHz range, dielectric constants of all tissues stay in the same range, whereas their conductivity values increase noticeably after 1 GHz. This phenomenon can also be seen in Figures 8, 9, and 10. As discussed in section (III-b), this is mainly due to the dielectric relaxation of water at microwave frequencies, especially after 1 GHz.

Table 1: (a) dielectric constant and (b) conductivity of various body tissues at 37°C [25]
Figure 8, 9, and 10 present some of the collected data by Gabriel and Gabriel [28] for liver, bone cancellous, and fat, respectively. Details of the tissue, measurement temperature, and the references are included in the legend of each figure. As it is shown in Figure 9, conductivity values at low frequencies (below GHz rage) are not significantly frequency dependent. The conductivity in this range is associated with fluid-filled channels that permeate the tissue, and is proportional to the conductivity of the medium surrounding it [3]. Adipose tissues, such as fat and bone marrow, are characterized by their low-water-content and by lipid-filled cells. As shown in Figure 10, they have large $\alpha$ dispersion, while $\beta$ dispersion is small in comparison with that of soft tissue, presented in Figure 8.
Figure 8: Dielectric properties (a) dielectric constant and (b) conductivity of liver [28]
Figure 9: Dielectric properties (a) dielectric constant and (b) conductivity of bone cancellous [28]
IV) CHALLENGES AND FUTURE WORKS

The interaction of radiofrequency and microwave electromagnetic waves with biological systems was reviewed in this paper. As discussed in section III-a, both thermal and non-thermal effects of RF and microwave interaction with biological tissues have been studied intensively over past decades. While the thermal effects are fairly well understood, weak microwave interaction mechanisms and non-thermal effects of EM waves on physiological behaviors of cells are still debatable and more research needs to be done in this area.

In some studies, the possibility of RF/microwaves acting as “promoting agents in inducing genetic changes in biosystems” has been discussed [29]. It seems that if this hypothesis is demonstrated to be true in humans, new exposure standards and SAR thresholds need to be determined. In such a case, the use of RF and microwaves for biomedical applications and medical treatment and diagnosis would be significantly restricted.

With today’s advances in technology and science, I believe that new techniques to measure dielectric properties of tissue in-vivo need to be developed. The majority of the
reliable dielectric property measurements that are used today are from a few decades ago [10,12,13,24,25]. A new series of experiments to measure dielectric properties, especially those of human organs, should be the next step toward better understanding of the interaction between RF/microwaves and biological tissues.
REFERENCES:


